Carbon Management in Agriculture

for mitigating greenhouse effect

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FOREWORD

Global climate change has already manifested itself through increase in global temperature by 0.6 to 0.8°C during the 20th Century and increase in frequency of extreme events like very high intensity precipitation, frequent droughts, heat waves etc. Carbon in the form of CH_4 and CO_2 is the major player in contributing to this global climatic shift. Soil being one of the potential sinks for global carbon stock (3.5%), soil carbon management holds the key for developing effective adaptation strategy that would sustain the agricultural production, environmental health *vis-à-vis* food security and livelihood. Adoption of appropriate package of practices, cropping systems, restoration of degraded lands, agroforestry interventions, conservation agriculture, integrated nutrient management etc. has great potential to sequester carbon and reduce the emission of methane, nitrous oxide and carbon dioxide to the atmosphere.

Carbon sequestration potential through adoption of recommended package of practices alone on agricultural soils is about 6 to 7 Tg/year. Novel approaches like *Biochar* production and application to soil would help in sequestering carbon and improvement in soil physical health. Further, the sizeable livestock population (485 million) in India needs special attention where concerted efforts have to be made on efficient maintenance level, quantity and quality of feed etc. for livestock so that methane emission is reduced by the bovine population (283 million) in particular. This also demands adequate measures such as proper blend of protein rich and crude fibre diets to contain the emission of methane and other GHGs from the livestock sector. Admittedly, comprehensive information on carbon management in agriculture is meager and compilation of scientific information on this burning issue is a great challenge. Realizing the need to address all climate related issues on priority, concerted efforts were made and proactive initiatives were taken up by the Indian Council of Agricultural Research through the implementation of National Initiative on Climate Resilient Agriculture (NICRA), a mega research programme in the XI Plan.

The editors and contributors deserve appreciation for bringing out this publication on "Carbon Management in Agriculture for Mitigating Greenhouse Effect". The entire team has done a commendable work in addressing all the issues in a very holistic manner cutting across the disciplinary boundaries. I am confident that this publication will be very useful for climate managers, researchers, planners and students of natural resource management interested in efficient carbon management as a strategy to develop climate resilient agriculture.

Dated the 12th July, 2012 **(S. Ayyappan)**
New Delhi

Preface

Soil carbon is considered one of the most important indicators of the productivity of low input farming systems and in assessing the soil health. It is the key to soil fertility, productivity and quality, as decline in carbon content not only affects sustainability of agricultural ecosystems, but also extremely important in maintaining overall quality of the environment. Soil contains a significant part (3.5%) of global carbon stock. There is a growing interest in assessing the role of soil as a sink for carbon under different landuse practices as increase in soil organic carbon content by 0.01% could lead to sequestration of carbon that can compensate the annual increase of atmospheric carbon dioxide concentration. Sequestering 1 tonne carbon in humus can conserve nutrients to the tune of 83.3 kg N, 20 kg P and 14.3 kg S per hectare. Thus, carbon management is the essential to environment management and sustainability of soil health *vis-a-vis* agricultural productivity.

Northeastern region of India, a mega-biodiversity centre of the world, contains more than one-third of India's total biodiversity. The region has huge potential of biomass production, well supported by complimentary climatic factors, more particularly high rainfall for luxuriant vegetative growth and regeneration rate. Availability of abundant phyto-biomass (both above and below ground) in the form of forests and other allied sources has made the north east region a unique place in the world. Since vegetation is one of the most important sources to enrich soil with carbon, a general belief is that the soils of NE region will be very high in carbon content cutting across all major landuse practices. However, in reality, prevalence of slash and burn agriculture (*jhuming*) in 0.877 Mha area of NE region resulted in burning of biomass of more than 8.5 million tonnes annually at the rate 10 t ha^{-1}. If this trend continues, sustainability of environment, soil health *vis-a-vis* agricultural production systems and food security of the region will be pushed to a real doldrums.

Realizing the importance of carbon management in agro-ecosystem in sustaining productivity, an eight days training programme on "C-management in Agriculture for mitigating green house effect" was organized by ICAR Research Complex for NEH Region under "National Initiative on Climate Resilient Agriculture" to sensitize and update the new frontiers of C-management strategies like conservation agriculture, biochar, mitigation of GHGs emission and other potential C-sequestration approaches. The present book is the outcome of the valuable contributions made by various scientists and researchers across the country. We hope, the book on ***"****Carbon Management in Agriculture for Mitigating*

Greenhouse Effect" will immensely help in the understanding the science of carbon dynamics and management in agro-ecosystems.

The authors are sincerely thankful to all the contributors for their valuable chapters without which it would not have been possible to bring out this publication. Special thanks goes to Miss Binalyn Kharumnuid for typesetting and arranging all the chapters of the book. Finally, the help rendered by the scientists, staffs and RA/SRFs are sincerely acknowledged.

Editors

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Climate Change and Food Security in North Eastern Region of India

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Introduction

It is generally accepted that our climate is changing due to increased concentration of green house gases. Global circulation models estimate the magnitude and time-scale of these changes and their effects on drought, floods, industry, agriculture etc. (Peiris *et al.*, 1996). Agriculture is the most vulnerable sector to climate change as it is inherently sensitive to climate variability particularly to rainfall and temperature induced aberrations. Global warming is expected to alter the area under major food crops around the world. For example, the area under cereal crops especially wheat may expand to north in Europe (Carter *et al*., 1996). Therefore, climate change will have considerable implecations on food production and livelihood security (Rosenzweig *et al*., 2001). It is reported that about two-third of the sown area in the country is drought-prone and around 40 million hectares are flood-prone. The poorest section of the society, inhabitant to geographically fragile locations, are likely to be most vulnerable to climate variability and change since they rely heavily on climate-sensitive sectors such as rainfed agriculture and fisheries (Samra *et al.,* 2004; Prasada and Rana, 2006). They are located geographically in more exposed or marginal areas, such as flood plains, hills and mountainous regions or degraded lands with sub-optimal productive capacity. Poor socio-economic condition further increases the vulnerability to abrupt climate change and subsequently, reduces the adoption capacity to mitigation and adaptation strategies against climate induced hazards.

The northeast India is equally vulnerable in terms of eco-fragility, marginality and inaccessibility making the future agricultural scenarios more uncertain and risk prone. The erratic pattern of rainfall (spatio-temporal), higher frequency of extreme rainfall events, less rain in June-Aug, and more in Sept/Oct, and more frequent flash floods and longer dry periods in various parts of the region manifests the impact of climate change (Borthakur *et al.*, 1989). Summer monsoon rainfall has been decreasing significantly during the last century at an approximate rate of 11 mm per decade. On the other hand, the annual mean maximum temperature in the region is rising at the rate of +0.11°C per decade. The annual mean temperature is also increasing at a rate of 0.04°C per decade in the region (Das, 2009). At the mid-altitude of Meghalaya, the maximum temperature is increasing linearly over the years whereas the minimum temperature showed a gradual decreasing trend and the gap between maximum and minimum temperatures are widening. Similar trend was also observed in other places of the region.

Climate change will make water availability more uncertain, both in time and space. While overall trends are difficult to decipher, there are clear indications that the frequency and magnitude of high intensity rainfall events are increasing in the NE region (Goswami *et al.,* 2006) with negative implications on infiltration and ground water recharge and also for long term soil moisture and water accessibility for plants. There are also indication that the dry season is becoming drier and seasonal droughts and water stress becoming more severe. The arrival time and length of monsoon season is also changing.

Agro-climatic conditions and status of food grain production in north east India

In Arunachal Pradesh, there are 5 agro-climatic zones and rice is the main crop of the state. Tropical and temperate fruits are also grown. In Assam, having 8 agro-climatic zones, double cropping of rice is practiced in the plains. Fish farming in large water bodies and marshy lands are also common. Among the plantation crops, tea husbandry is most common enterprise in the state of Assam. Manipur having 3 agro-ecozones, rice, fruits, vegetables, spices are major crops grown. Meghalaya has got 5 different agro-ecozones and rice, maize, ginger, turmeric, citrus etc. are the important crops grown. Rice is grown in terraces of Mizoram (3 agroecoregions) with horticultural crops in sloppy lands. Nagaland has got 4 climatic zones where rice is cultivated in the valleys and horticultural/plantation crops in the hills. In Sikkim (4 agroclimatic zones), where agriculture is well established in bench terraces, maize, horticultural/plantation crops are grown. Large cardamom and temperate orchids are also grown extensively in Sikkim. In Tripura, there are 3 agro-ecoregions, where double

Table 1 Food grain production and requirement scenario of the NE States

State	Production (000 t) (Triennial from 2008-10)	Requirement (000 t)	Deficit/surplus (000 t)	Deficit/surplus (%)
Arunachal Pradesh	250.4	268.1	-17.7	-6
Assam	3714.2	6043.1	-2328.9	-38
Manipur	356.1	427.3	-71.2	-16
Meghalaya	233.7	574.7	-341	-59
Mizoram	65.2	211.5	-146.4	-69
Nagaland	491.5	384.0	107.5	28
Sikkim	105.6	117.8	-12.2	-10
Tripura	637.6	711.7	-74.2	-10
Total NE	5828.6	7202.9	-1374.3	-19

cropping of rice is prevalent in the plains. Pigeonpea, black gram, lentil, sesame, mustard, pineapple, arecanut, tea and vegetables are also grown.

The data on food grain production and requirement indicate that there is a deficit in all the NE states varying from 10% for Tripura/Sikkim to 69% for Mizoram, except Nagaland with 28% surplus in food grains (Table 1). Presently, the region as a whole is deficit of about 1.4 million tones of food grains (19 % deficiency). The projected food grain demand for NE region is 15.24 million tonnes and 16.75 mt for the year 2021 and 2025, respectively**.** Frequent occurrence of drought-flood cycles, extreme events of precipitation, prevalence of diseases and pests, their complex interaction supported by favourable environment (high humidity, mild temperature and high rainfall condition) has been threatening the agricultural production systems *vis-à-vis* food security in the region. The drought of 2009 is believed to have reduced rice production by about 20-30% in the north eastern region. Similarly, in the livestock sector, large deficiency in fish (54%), milk (62%), egg (85%) and meat (58%) production further complicated the supply of balanced nutrition in the region (Table 2).

Table 2 Fish, milk, eggs and meat production and requirement scenario for NE region

Commodity	Production (000 t) (Triennial from 2008-10)	Requirement (000 t)	Deficit/surplus (000 t)	Deficit/surplus (%)
Fish	272.7	592.6	-320.0	-54
Milk	1244.0	3327.9	-2083.0	-62
Eggs	9894.0	68682.0	-58488.0	-85
Meat	206.0	501.0	-295.5	-58

N.B: Fish and meet requirement has been worked out @ 13 kg & 11 kg/person/year

In order to make the region self sufficient in food grain production, the productivity of all the food crops has to be increased from the present low level with effective utilization of natural resources under the existing climate-topography-landuse patterns across NE region. Effective utilization of natural resources coupled with use of high yielding varieties and optimum package of practices would certainly reduce the gap to a great extent.

Climate change and agriculture – Some evidences from North East India

The abnormalities in weather are causing a lot of damage to the agriculture and horticultural crops in the region. The recent example is the year 2009, where rainfall during monsoon months was very scanty and farmers could not take up their sowing activities. Those who had undertaken the sowing; their crops either failed to germinate or died due severe moisture stress causing huge damage to the livelihood of the farmers. It was predicted that the productivity of *kharif* crops were reduced by 20-30%, depending upon the severity of drought and type of crops grown by the farmers. Several districts of Assam were badly affected due to drought like situations consecutively for two years in 2005 and 2006, which had a signature of climate change on them as vindicated by the IPCC report of 2007 (IPCC, 2007). The year 2005 saw prolonged dry periods in Mizoram with many springs and streams dried up accompanied by large scale landslides (ICIMOD, 2008). A similar drought and extreme events in other parts of NE India was also recorded during the year 2009.

Mountains are among the most fragile environments on earth. They are rich repository of biodiversity, water, and providers of ecosystem goods and services on which downstream communities rely. Mountain regions occupy about one –fifth of the Earth's surface and are home to one –tenth of the global population. Indian Himalayas cover 16 per cent of the geographical area and out of the 21 agro-ecological regions as in India, the Himalayan regions have cold arid and warm sub humid to humid climate. Several agro-climatic zones, *viz*., Alpine zones, Temperate Zones, Sub- tropical hill zone, Sub –tropical plain zone, Mild tropical humid hill zone, Mild tropical humid plain zone are present in the region. The debate on climate change is on and the effect of climate change on the region is of high magnitude. The hill and mountain farmers are expected to be more vulnerable to any shift in climate due to their dependence on natural resources, poor risk bearing ability and lack of credits.

Interview with the farmers and experts revealed that the *khasi* mandarin growth in the NE region of India is the worst sufferer of climate change. While there are many factors for citrus decline, shift in climatic behaviour are seen as major factor of declining its growth and productivity. Fruit fly in guava is becoming alarming due to hot and humid condition. There is advancement in flowering of guava and peach by about 10-15 days due to increase in temperature at mid altitudes. The crops like peach, plum etc. which require low chilling are also showing the sign of decline in productivity. In cucurbitaceous vegetable crops particularly ash gourd, bottle gourd and pumpkin, there is decline in yield due to increase in vegetative growth and poor production of female flowers which is believed to be due to warm and humid climate in mid altitudes of Meghalaya. In rhizomatous crops like colocasia there is excess vegetative growth in early growth stages. Climatic condition (warm and humid) is favourable for pests like beetles, bugs and other sucking pests and diseases like blasts, blight etc., leading to reduction in production of corms and cormels. It has also been recorded that the pest ecology of certain crops is changing due to climate change. The tree bean (*Parkia roxborghii*) which was earlier grown up to an altitude of 950 m msl, are now growing up to 1300 m indicating the increase in temperature at higher altitudes. The farmers from Ri-Bhoi district, Meghalaya explained that their banana growth is now much better than the earlier days and they are now getting higher productivity due to increase in temperature.

Fisheries sector is also vulnerable to climate change. Crops have the ability to adapt to extreme climate variability even up to 4^0C temperature while fishes and animals do not. Drought coupled with increase in temperature results poor fish breeding and death of fish spawns, fry and fingerlings. A similar case was reported from *Son Bill*, Karimganj (Assam) during the drought experienced in 2009.

Greenhouse gases and their management

Amongst various GHGs that contribute to global warming, carbon dioxide is released from agriculture by way of burning of fossil fuel for agricultural operations; methane is emitted through agricultural practices like inundated paddy fields, nitrous oxide through fertilizers, combustion of fossil fuels etc. Nitrous oxide has a global warming potential 296 times greater than CO_2. In India, it is estimated that 28% of the GHG emissions are from agriculture; about 78% of methane and nitrous oxide emissions are also estimated to be from agriculture.

As per the IPCC, every quintal of nitrogen applied in farming emits 1.25 kg of nitrous oxide. Half of the nitrogen applied to crops is lost to the environment. Burning of crop residues also impacts the soil fertility. Heat from burning straw penetrates into the soil up to 1 cm, elevating the temperature as high as 33.8–42.2°C. Of the world's total emission of 16-34 Teragram (Tg) from rice cultivation alone, India contributes 2.4-6.0 Tg. The average methane flux from paddies ranges from 9 to 46 g/m^2 over a growing periods of 120 to 150 days. In 0.88 M ha slash and burn practice of shifting cultivation in NE region, about 10 t biomass per ha is burnt every year which contributes enormous CO_2 emission to the atmosphere.

The livestock sector is another major contributor to the production of GHGs. For the year 1997, livestock contributed 9.0 Tg methane and 1 Gg nitrous oxide which in terms of CO_2 equivalent is around 190 Tg. About 21 million livestock population in NE region mainly local non-descriptive type is also responsible for methane and nitrous oxide emissions. About 0.665 mt of CH_4 emission is likely to be released from the livestock sector in NEH Region.

From rice cultivation in NE region, about 0.51 mt of CH_4 emission is expected. Changes in farming models and practices towards sustainable agriculture offer significant opportunity for reducing GHG emissions. SRI and aerobic rice cultivation offers scope for significant reduction in methane emission from rice fields. Organic farms use on an average 30 to 50 per cent less energy as compared to the conventional agriculture (Ziesemer, 2007). Energy efficiency (energy produced/energy used) is also better in organic agriculture (Pretty, 1995; Stolze *et al.*, 2000; Hoeppner *et al.*, 2006). Energy consumption through use of fertilizers could be anywhere between 25-68 percent of the total energy use depending on the types of crops and growing conditions (Refsgaard *et al.*, 1998). Residue recycling, legume production, crop rotation, mixed cropping, biological pest management etc., also reduce GHG emission. Sustainable agricultural practices increase the soil organic carbon by incorporating organic materials into the soil. Soil can be a major source of storage of carbon, about twice as much carbon as in the atmosphere. Crop, tree and livestock integration with a systematic recycling of organic wastes is an integral part of sustainable agriculture and helps in reducing GHG emission. Conservation agriculture involving reduced tillage and residue recycling promote sequestration of carbon dioxide and thereby reduce global warming. In the rainfed agricultural system of NE India, system of rice intensification is a feasible alternative to the existing practice of cultivation in continuous submerged conditions since SRI can cope with irregular intervals of rainfall and thus methane emission can be reduced in the anaerobic-aerobic transformation cycle. Agro-forestry is also a desired practice which further adds to the potential of sustainable agriculture in carbon sequestration.

State wise major climate risks in NE Region

Assam - Floods, marshy land, droughts, terminal heat stress, cyclones; **Arunachal Pradesh-** Drought, landslides, floods, low temperature; **Meghalaya-** Drought, erosion and soil loss, frost/low temperature; **Mizoram-** Drought, landslides; **Manipur-** Drought, floods, landslides; **Nagaland-** Drought, erosion and soil loss; **Tripura-** Droughts, terminal heat stress, floods, cyclones; **Sikkim-** Low temperature, landslides

Constraints for agriculture and livelihood in North Eastern Himalayas

Production constraints

- Difficult agro-ecological conditions (e.g., poor soil health, soil depth, erratic distribution of rainfall, steep slopes, short growing seasons and extreme climates),
- Poor infrastructure, communication and transport, and service support (e.g., roads, irrigation, markets, research and extension, credit, schools and health centers),
- Poor socio-economic status of inhabitants (e.g., small and scattered land holdings, poor resource base etc),
- Dominance of rainfed agriculture.

Hydrological constraints

- Large variability in the amount, frequency and distribution pattern of rainfall makes agricultural operations and crop yields uncertain and highly risk prone,
- Excess water during monsoon period, causing runoff, soil erosion and floods and water deficit during the sowing time of crops in *Rabi.*
- Undulating topography – a major constraint in the development of irrigation facilities in the hills.

Water constraints

- Annual average rainfall of the region is around 2450 mm accounting for 10 per cent (42.0 M ha m) of country's total water of 420 M ha m.
- Unfortunately, it could utilize only 0.88 M ha m of water till date.
- Remaining 41.12 M ha m water is lost annually through runoff along the steep slopes primarily due to dominance of undulating hilly topography.
- At hilltop, the land is left absolutely fallow almost for 6-7 months during post-rainy season due to severe water scarcity.

Water and climate induced hazards: concerns for NE India

- With glacial contribution deceasing over the years, in future, lean season flow will decrease and water stress will increase in the Brahmaputra basin where large populations depend on agriculture for livelihood.

- The southern part of *Nagaon* district in central Assam valley and adjoining parts of *Karbi Anglong* form a rain-shadow zone where annual rainfall is as low as 800-1200 mm. Water scarcity is a potential constraint for the people living in this rain shadow zone and absence of effective irrigation systems or water harvesting practices adds to the vulnerability of the people.
- Rainfall in this zone is decreasing slowly as found in *Lumding* where rainfall is on the decline at the rate of 2.15 mm per year. In some years floods have affected more than 3.8 million hectares of Assam's total area of 7.8 million hectares (WB 2007).
- Floods inundate at least 2,000 villages every year in addition to destroying other infrastructure. The problem is further aggravated by riverbank erosion, which destroys about 8,000 hectares of riparian land along the Brahmaputra annually. Vast areas in the region have been affected by erosion e.g., 1 million hectares in Assam; 815,000 hectares in Meghalaya; 508,000 hectares in Nagaland; 108,000 hectares in Tripura; and 14,000 hectares in Manipur (Venkatachary *et al*., 2001).
- Due to construction and infrastructure development, there is encroachment in tribal habitats which is resulting in loss of biodiversity and indigenous culture. Deforestation is at alarming rate. The water bodies are frequently encroached for infrastructure and housing leaving little scope for livelihood of fisherman.
- Given the high probability of increased extreme rainfall events, landslides, formation of glacial lake outburst floods (GLOF) and landslide dam outburst floods (LDOF) due to climate change in the Himalayan region, threats of flash floods will always loom large from the large dams in Arunachal Pradesh, Bhutan and Sikkim for the downstream populations in Assam and North Bengal.
- There is indiscriminate felling of trees in almost all the states in and outside the forest areas. The forest fire and *jhum* burning also is causing loss of flora and fauna. The indigenous ethnic tribes who depend on the forest for centuries, suddenly finding no option for their livelihood resulting in unrest in some pockets.

Shifting cultivation: Impact on soil, water, climate and productivity

- About 0.88 million hectare is still under shifting cultivation i.e., slash and burn agriculture in the NE region.
- At least 10 t biomass per ha is burnt annually in such cultivation practices leading to release of huge amount of carbon monoxide and CO_2 to the atmosphere.
- Large scale deforestation is resulting in denudation of hill tops and slopes. Since the hill tops are the source of water, deforestation of hill top leads to elimination of the source of water.
- There is large scale soil erosion due to deforestation and cultivation on hill slopes without effective soil conservation practices.

- Erosion of soil in catchment area resulting in siltation of reservoirs and streams, leading to frequent floods on the plain/low-lying areas.
- Removal of top soil leads to loss of fertility, shallow soil depth, which is not easily built up. This leads to low productivity and subsequent pressure on land.
- Annual soil loss to the tune of 46 t/ha due to cultivation in steep slopes and removal/ burning of biomass from surface.
- Reduction of *jhum* cycle to 2-3 years from the earlier 10-15 years is causing further land degradation as there is less time left for restoration of soil fertility.

Strategies for bridging food grain deficiency

Following strategies can be followed to bridge food grain deficiency in NEH Region:

- Developing rice variety with an average yields of 2.2 t ha^{-1} from the present yields of 1.8 t ha^{-1} i.e., a gain of 1.4 mt production from 3.5 mha of rice area.
- Development of rice varieties for shifting cultivation areas to achieve yield of 1.2 t ha^{-1} from the present level of 0.7 t ha^{-1}. Improving rice productivity in *jhum* fields by about 0.25 t ha^{-1} would give another 0.22 million tones.
- Introducing double cropping in 25 – 30% valley land areas of the 1.5 mha to gain a production of 1.12 mt.
- To promote irrigation facility together with state department through Bharat Nirman Programme to get additional 1 mt production.
- Similarly, facilitation of additional production of 0.67 lakh ton of maize by increasing productivity from 1.5 t ha^{-1} to 2.2 t ha^{-1} from 0.96 lakh ha area under maize cultivation.

Mitigating abiotic stress through tolerant crop varieties in NEH Region

Tolerant varieties of crops have been identified over the years for cultivation in the NE region. Major abiotic stresses in the region are drought, water logging, cold, soil acidity induced iron and aluminium toxicity problems. Some of the potential varieties identified are-

Field crops

Soil acidity

Rice varieties: Bhalum 1, Bhalum 2, Bhalum 3, Bhalum 4 and Maniphou 6 (Al toxicity in Upland), RC Maniohou 7 & RC Maniohou 11(Fe toxicity in lowlands).
Maize varieties: Maize RCM 1-1 and Maize RCM 1-3
Cold stress - Megha Rice 1, Megha Rice 2 and Megha Rice 3
Iron toxicity - Shahsarang 1 & Lampanah

Vegetables

Soil acidity: Manikhamnu, Manileima, Manithoibi (tomato in Manipur)
Moisture stress: RCDL 10 (Dolichos/lablab bean), RCFBL 1 (French bean pole type)

Cold stress: Megha tomato 3 (Tomato)

Spices

Soil acidity: Megha Turmeric 1 (Turmeric)

Fruits

Moisture stress: TA 170 (Peach), Kaveri (Passion fruit)

Evaluated/identified varieties for abiotic stress (Soil acidity, moisture stress)
Ranjit, Naveen, IR 64, Vivek Dhan 82 (Rice), ICGS 76, ICGS 44 (Groundnut), JS 335, JS-80-21 (Soybean), TS 36, TS 38, TS 46 (Toria), Nadia, Varada (Ginger)

Strategies for contingency management plans for drought in North East India

During last decade, it was observed that due to drought, there was severe toll in food grain production. Following contingency plan may be followed to reduce the impact of drought on Northeast agriculture.

- Crop diversification: In low to mid altitudes, short duration crops such as maize, finger millet, green gram, black gram, chick pea, rice bean, soybean, sunflower, sesame etc. may be grown.
- In lowland plain areas of Assam, short duration and high yielding rice varieties like Vivek Dhan-82, VL Dhan-61, IET-19628 etc. may be encouraged. These varieties are equally good in mid-altitudes where transplanting should be completed by mid-August.
- When drought extends up to mid - August, system of rice intensification (SRI) method in Tripura and Assam valley may be adapted where requirement of nursery area and water are less and crop duration reduced by about 15 days.
- Crop varieties such as black gram (T-9, PD 4), greengram (TS-37, Meha), rajmash/ frenchbean (Naga local, Mizo local), sesame (T-1686, maize (Vijay composite), soybean (JS 335, JS 80-21), ricebean (RBS 16, RCRB 1-6, PRR 2), may be undertaken instead of upland rice.
- In flood prone areas of Dhubri, Nagaon, Dhemaji and North Lakhimpur districts of Assam, where drought is also equally affecting rice cultivation, boro rice is recommended and shallow tube wells will help not only in providing life saving irrigation but also drinking water.
- If severe drought prolongs till the end of August, pre-*rabi* cops can be grown. In case of severe stress, mulching with biomass or polythene (8-10 micron) and application of organic manure (FYM, vermi-compost, green manure etc.) for in-*situ* conservation of soil moisture may be adapted.

Improved resource management practices for climate resilience agriculture

Jhum – Improvement approach

- Contour bunding, toposequential cropping and use of high yielding crop varieties.

- Inclusion of leguminous crops like ricebean, groundnut as cover crops and hedge row species like *Tephrosia, Indigofera* spp on boundaries, contours to reduce erosion and rehabilitate degraded *jhum* land.
- Use of fertilizer and manure to improve productivity.
- Adoption of proper crop rotation and introduction of non-traditional crops (wheat, barley, peas etc.) after traditional crops (rice, maize, millet)
- Cash crop horticultural development in abandoned *Jhum* land
- For long-term sustainability, viable alternative farming system strategies like agri-horti-pastoral system, terraced cultivation etc. has to be followed.
- Plantation of trees (e.g., *Parkia roxburghii*, Alder) with *Jhum* crop for rehabilitation of degraded soils and to supply additional income from agricultural crops (like beans).

Micro-watershed based farming system approach: Farming system requires integrated or holistic approach in sustaining productivity of hill agriculture (Satapathy and Sharma, 2006). In natural resource conservation, different topo-sequential cropping involving Agri-horti-silvi- pastoral system was found to be most economical under effective soil and water conservation measures in the northeast. It is also possible to integrate different components of ecosystem (land, water, plant species etc.) to obtain sustained production from waste, rainfed and degraded lands to check natural hazards like floods, drought and soil erosion.

Agro-pastoral based land use system was adopted on hill slope up to 50 per cent with bench terrace, and contour bunding as major soil conservation measures. Land development under the system may cost about 400 - 500 mandays ha^{-1}. Hilltops should be kept under forest (fuel-cum-fodder trees, bamboo and timber trees etc.). Analysis of sustainability and livelihood potential showed that the system incorporates the classical organic recycling and non competitive inputs, arresting nutrient in rainwater flow by growing forage crops on the terrace rises, negligible soil erosion and converting in a chain all biomass in the watershed into economic outputs.

Agri-horti-silvi-pastoral land use systems comprise agricultural land use towards the foot-hills, horticulture in the mid portion of the hill and silvi-pastoral crops in top portion of hill slopes. Contour bunds, bench terrace, half moon terrace, grassed ways are the major conservation measures. Such land uses are expected to retain over 70-90 per cent of the annual rainfall with negligible soil erosion. This is an integrated system capable of providing full time and effective employment to a farm family.

Farming system approach: Within an agro-ecological zone, several farming systems involving complementarities of crop-animal-horticulture-fishery-agroforestry are found in the hills with variation in resource endowment, preferences, and socio-economic position of the specific family. Sound soil conservation and soil management practices should be an integral part of such farming system, to suit the specific location conditions of the varying elevations of hills. In economic terms, there is great potential for the development of commercial production of tree and perennial crops (large cardamom, tea, coffee, black pepper etc.) on the slopes for export market.

Maintenance of soil fertility: The relationship between soil erosion, nutrient, runoff losses, organic matter depletion, and beneficial effects of conservation and management practices occur simultaneously. Soil fertility remains at an optimum level if regular doses of manure and fertilizers are added to it and soil pH adjusted to 5.5 to eliminate the aluminum toxicity. Multiple cropping, inter-cropping, relay cropping, inclusion of legumes in rotation, strip cropping etc. ensure better crop productivity, besides maintaining soil fertility. Plant nutrients in crop residues, litter from forests, cattle manure and domestic-waste composts comprise the working capital of plant nutrients because farmers can transfer and allocate those nutrient sources to a particular crop in a crop rotation and to a particular plot. The integrated plant nutrient system (IPNS) is a step in the direction of sustainable agricultural development through necessary modification of the conventional technology to improve soil health by adopting the best time, method and source of application and utilizing sources other than chemical fertilizers such as organic manure, bio-fertilizers etc. to meet part of the nutrient needs of crops and cropping system.

Amelioration of acid soils: Acid soils occupy nearly 81% geographical area in the NE region of India. Acidic soil below pH 5.5 occupies around 16.2 mha. The productivity of such acid soil hardly goes above 1 t ha^{-1}. Furrow application of high quality, uniform grades /sizes of lime 250-500 kg ha^{-1} at furrows every year can optimize the yields of crops in acid soils of NEH Region. Use of acid tolerant varieties and application of organic manure also improves productivity of such soils.

Organic farming: Less use of fertilizers and agrochemicals coupled with availability of sufficient biomass (46 mt of manure), which is almost equivalent to the requirement for organic production in identified areas. Vermicomposting, green manuring, growing of leguminous hedge row species viz., *Crotolaria, Flemingia* sp. in the bunds, farm fences and terrace/risers, recycling the pruned biomass in to the field improves soil health and productivity and reduces dependence on external inputs.

***In-situ* residue management:** Effective management of residues, roots, stubbles and weed biomass can have beneficial effects on soil fertility through addition of organic matter, plant nutrient and improvement in soil condition. Incorporation of crop residues not only improve crop yield but also increase the nutrient uptake besides improving the physico-chemical and biological properties of the soil which provide better soil environment for growth and development. The soil biological properties like population of *Rhizobium*, bacteria, phosphorus solubilizing microorganism and earthworm activity improves remarkably when residues are effectively recycled.

Alley cropping/Hedge row intercropping: Intercropping in interspaces of hedgerow is a proven and sustainable technology for the NEH Region. Depending upon the slopes, plant species involved, the alley width may vary from 2-5 m. In north east India, leguminous shrubs like *Crotolaria, Tephrosia, Cajanus cajan, Flemingia, Indigofera sp.* etc. are suitable as alley crop or hedge row crop. Ginger, turmeric, maize etc. are grown in between the alley. The green biomass (leaf, twigs etc.) of such hedge row species are very rich in plant nutrients especially N, P and K. This system of cultivation reduces erosion and conserves soil moisture and nutrients. On an average, pruning of N fixing hedgerow species add 20-80, 3-4 and 8-38 kg ha^{-1} $year^{-1}$ of N, P and K, respectively.

Conservation tillage system: Conventional tillage results fine tilth in surface while compaction at sub-surface layers and thus results in huge soil loss during heavy rains owing to finer soil particles, low infiltration and higher runoff along the steep slopes. Conservation tillage can reduce soil loss by 50 per cent and conserves soil moisture to a great extent. The experimental results reaffirmed that conservation agriculture maintains or improves productivity, gives higher return and conserves soil and water and improves overall soil quality. Crops like rice, maize, pea, lentil and toria are grown profitably in NEH Region following CA approaches.

Watershed approach: Watershed management as an approach for soil and water conservation measures and for socioeconomic development of community is already a widely accepted fact. Watershed approach reduces farmer's risks by integrating various enterprises, harvesting rain water and using harvested water for life saving irrigation during lean periods. Percolation tanks, gully control measures, terracing etc. are some of the important mechanical measures in integrated watershed approach.

Jalkund-a micro rainwater harvesting structure: *Jalkund* (a rainwater harvesting structure in India) technology is found effective for rain water harvesting in hill tops. The steps for making *Jalkund* are: digging a 5 x 4 x 1.5 m pit, leveling the sides and corner of *Jalkund*, smoothening of walls of *Jalkund* by plastering with mixture of clay and cow dung in the ratio of 5:1, cushioning of *Jalkund* with dry pine leaf/hardy grasses @ 2 to 3 kg m^{-2} and finally laying out silpaulin sheet (250 micron thick) for covering the *Jalkund*. The harvested water (about 30,000 litres at one time) is used for life saving irrigation, animal husbandry and domestic uses.

Land configuration for increasing cropping intensity: In North East India, due to very high rainfall, proper drainage is a problem especially during rainy season. Even in winter season, the water table in the foot hills remain high mainly because of seepage from surrounding hillocks and uplands. In permanent raised and sunken beds, the raised area is used for cultivation of vegetables and other remunerative crops whereas, sunken area is used for double cropping of rice. The land utilization is 100 percent in these systems. For temporary system, after harvesting *kharif* rice, temporary raised beds are constructed to cultivate vegetables. Under mid altitude condition of Meghalaya, it was possible to achieve 300 percent cropping intensity on raised beds (tomato/potato/frenchbean/carrot–Bhindi–Frenchbean/black gram) and 200 % cropping intensity on sunken beds (rice transplanted– rice ratoon/lentil/

pea). About 1 lakh hectare of marshy land available in the NE region could be benefited from such land configurations.

SRI -an alternative method of rice cultivation: The SRI technology involves planting younger seedlings, wider spacing, frequent mechanical disturbances and alternate wetting and drying of fields. It requires less water. Since the field is kept soaked instead of flooding, the seedlings become stronger and there is better root growth. As a result the SRI, rice can tolerate water stress to a great extent compared to conventionally grown rice. These practices can improve rice productivity by 15-20 per cent over conventional practices. In Garo Hills, Meghalaya, similar results were obtained. Under mid hills condition of Meghalaya, SRI and ICM gives 10- 20 percent higher productivity compared to conventional practices. The significant aspect of these practices is that the crop duration gets shortened by about 10-15 days.

Agroforestry approach: Agroforestry is a most viable alternative for resource conservation and improving productivity in Eastern Himalayas including NE Region of India. Depending upon the slopes, climates and local needs, viable agroforestry models have been developed by ICAR Research Complex for NEH Region in different NEH States. Adoption of such models reduces runoff and soil loss substantially besides improving productivity and farm income in long run. Some MPTs like *Parkia roxborghii, Alnus nepalensis, Leucaenea lucocephala,* Bamboo etc. are important agroforestry species of the region.

Effective irrigation methods: Irrigation potential in the region has remained by and large most unexploited. As a result, more than 80 % area is rainfed and cropping intensity is around 120%. Development of water resources (watershed, medium & minor irrigation projects, tube well etc.) and their effective utilization is the key for success of agriculture in climate change scenario. Efficient irrigation methods like drip irrigation and sprinkler irrigation should be popularized for efficient water use and higher water productivity.

Integrated mountain development: Integrated mountain development includes a policy approach in planning and development of all sectors of energy, transport, tourism, industry, agriculture, horticulture, social issues of population policy, public health, education, and resource conservation techniques. It is a process whereby optimum use of mountain resources can be sustained over several generations in the context of available technology. It also includes preservation of gene pool, augmentation of the well being of the local people, controlled and acceptable downstream effects. Major efforts are needed to diversify the mountain economy and living standard of people with emphasis on hill environmental protection and sustainable development.

Indigenous technical knowledge: The validation of indigenous knowledge based on latest technical know-how by inter-generations wisdom of local inhabitants of the region through native means to suit their conditions.

Available options to address climate change

Mitigation

Since agricultural activities generate considerable amount of greenhouse gases. Food and Agriculture Organization (FAO) and International Research Centres of Consultative Group on International Agricultural Research (CGIAR) at international level and the Indian Council of Agricultural Research (ICAR) in India have developed mitigation plans. The major approach for devising mitigation strategies in India are:

i. Improving inventories of emissions of greenhouse gases using state of art emission equipment's coupled with simulation models and GIS for up scaling.
ii. Evaluation of carbon sequestration potential of different land use systems including opportunities offered by conservation agriculture and agro-forestry.
iii. Critically evaluating the mitigate potential of bio-fuels; enhance this by their genetic improvement and use of engineered microbes.
iv. Identifying cost-effective opportunities for reducing methane generation and emission in ruminants by modification of diet, and in rice paddies by water and nutrient management. Renew focus on nitrogen fertilizer use efficiency with added dimension of nitrous oxides mitigation.
v. Assessment of biophysical and socio-economic implications of proposed GHG mitigation interventions before developing policy for their implementation.

Adaptation

In the absence of adequate vulnerability assessment which is the key requirement to know the possible impact of climate change and implement adaptation strategies and policies, following strategies may be adopted for the North East India. These practices conserve natural resources, effectively utilize locally available resources, increases farmers' income and maintain balance in ecosystems. Some of such feasible options are-

- Altering sowing time/agronomic practices to cope up with changes in climate
- Switching cropping sequences/changing varieties/crops to suit current climate situation
- Water harvesting – Watershed approach, *Jalkund* (micro-rain water harvesting structure for hills), roof water harvesting for life saving irrigation
- Diversifying income through integrated farming systems to reduce climate risks
- Devising location specific technologies
- Improving jhuming by incorporating soil and water conservation measures, improved varieties and agronomic practices.
- Governmental and institutional policies and programmes

Research initiatives

1. Seasonal weather forecast to facilitate preparation of contingency plans for likely

temperature and rainfall regimes. Timely availability of seeds of suitable crop varieties and other required inputs has to be ensured.

2. Efforts proposed to convert C_3 crop plants (e.g., rice & wheat relatively meager utilization of energy and nutrition) like those of wheat and rice to C_4 (better utilizers) types like those of sugarcane and maize, for boosting the inherent production potential of important crops under CO_2 enriched condition.
3. In-situ and ex-situ soil and water conservation along with stress tolerant strains of crops and animal for climate resilient agriculture. Research works carried out to develop better water management schedules for paddy fields e.g., system of rice intensification (SRI), integrated crop management (ICM), alternate wetting and drying (AWD), raised beds etc.
4. A new fungus *Cyllamyces icaris* which has the ability to degrade dietary fibre thus reduces generation of CH_4 in ruminant/stomach. It improves utilization of fibrous crop residues like straw and stubbles which are used widely in the country as animal feed.
5. Initiative focused on Agroforestry in reversing the climate change forces is the need of the hour. Agroforestry systems involving trees and crops together or in sequence have the potential to serve as carbon sink to reduce the load of harmful gases. Evolving new plant species having good potential for sucking CO_2 to mitigate climate change effect.
6. Enhancing efficient use of N fertilizer and water and measures for reducing the emission of GHGs from agriculture and livestock sector. Research on coating of urea with neem or the use of neem cake for curtailing release of nitrous oxide. Apart from this, ICAR has suggested the Govt. fertilizer pricing policies with inbuilt incentive for fertilizers producers to churn out slow nutrient releasing products to reduce loses in the form of gases as well as through leaching.

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Carbon Sequestration in Agricultural Soils: Evolving Concepts, Issues and Strategies

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Introduction

Soils are the largest carbon reservoirs of the terrestrial carbon cycle. Soil, if managed properly, can serve as a sink for atmospheric carbon dioxide. As the atmospheric CO_2 concentration continues to increase globally, more attention is being focused on the soil as a possible sink for atmospheric CO_2. There is every possibility that atmospheric carbon dioxide concentration would increase in the near future. Under such circumstances, soil will remain a potent sink for atmospheric carbon-dioxide. The global soil organic carbon storage corresponds to 615 Gt C in the top 0.2 m depth and 2344 Gt C in depths of up to 3 m, which is more than the combined C content of biomass and atmospheric CO_2. Soils constitute the largest pool of actively cycling carbon (C) in terrestrial ecosystems and stock about 1500-2000 Gt C (to a depth of 1 m) in various organic forms ranging from recent plant litter to charcoal, to very old, humified compounds and 800 to 1000 Gt as inorganic carbon or carbonate carbon. The total quantity of CO_2-C exchanged annually between the land and atmosphere as gross primary productivity is estimated at ~120 Gt C yr^{-1} and about half of it is released by plant respiration. Soils are the largest carbon reservoirs of the terrestrial carbon. Soils contain 3.5% of the earth's carbon reserves, compared with 1.7% in the atmosphere, 8.9% in fossil fuels, 1.0% in biota and 84.9% in the oceans (Lal, 1995). Mean residence time of soil organic carbon pools have the slowest turnover rates in terrestrial ecosystems and thus C sequestration in soils has the potential to mitigate CO_2 emission to the atmosphere. Furthermore, higher carbon stabilization in soil is benefitting the other ecosystem functioning like improvement in soil structure, water holding capacity, nutrient retention, buffering capacity and greater availability of substrates for soil organisms. However, little is known about the actual achievable carbon level in soil under different agro-ecological regions of the country.

The amount of organic carbon stored in various soil pools is the balance between the rate of soil organic carbon input and the rate of mineralization in each of the organic carbon pools. However, the storage of carbon in soil profile is governed by the soil type, climate, management, mineral composition, topography, soil organisms and other unknown factors. Carbon sequestration potential of different soils also vary with the clay content. It is suggested that if a soil has very high silt+clay content, the potential for soil carbon sequestration would be very high. But, in true sense, the potential for soil carbon sequestration is generally limited by the climate (rainfall and temperature) and the net primary productivity of the region. For example, the soils of dryland (vertisol) which contains appreciable amount of silt+clay contents had high carbon sequestration potential but in reality it would be difficult to attain the true level because of other limiting factors like rainfall, temperature and net primary productivity of the region. It means, a soil may have high carbon sequestration potential that would be achieved only if other factors are non-limiting. In the subsequent sections, we are trying to highlight some of recent developments in soil carbon research and terminology, which will help the readers in developing sound strategy for carbon sequestration in agricultural soils.

Concepts of soil carbon saturation and related implications

The soil carbon saturation suggests a limit to the whole soil organic carbon (SOC) accumulation determined by the inherent physicochemical characteristics of four soil C pools: unprotected, physically protected, chemically protected, and biochemically protected (Stewart, 2007). The relationship between soil structure and the ability of soil to stabilize soil organic matter (SOM) is the key element in soil C dynamics but very few models have taken cognizance of this fact (Six *et al*., 2002). Native soil C levels reflect the balance of C inputs and C losses under native conditions (*i.e*., productivity, moisture and temperature regimes), but do not necessarily represent an upper limit in soil C stocks. Most SOC models assume a linear increase in C content with C input, and thus C sequestration can continue regardless of the amount of organic carbon already contained in each SOC pools. Contrary to this, in many long term experiments, soils rich in C did not show any further increase in SOC following an enhanced C input. These findings suggest that there exists a soil carbon saturation limit. The difference between a soil's theoretical saturation level and the current carbon content of the soil is defined as saturation deficit (Stewart *et al*., 2007). Hassink (1997) reported C saturation of the silt + clay protective capacity, but not the whole soil. This occurs because C is retained in the labile (unprotected) state, which is subject to a faster rate of decomposition as the recalcitrant pool approaches saturation. This repot clearly suggests that soil has a definite capacity to capture or sequester organic carbon, beyond which the added carbon would escape to the atmosphere.

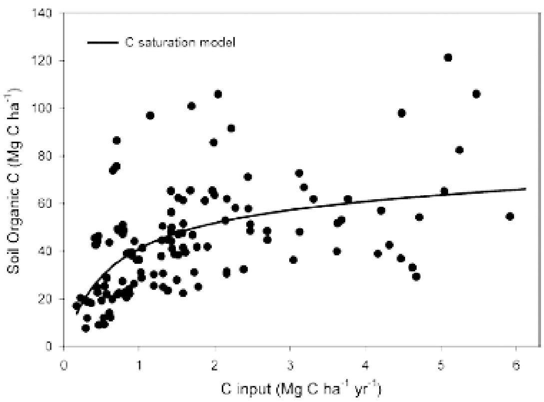


Fig 1 Soil carbon saturation evidence

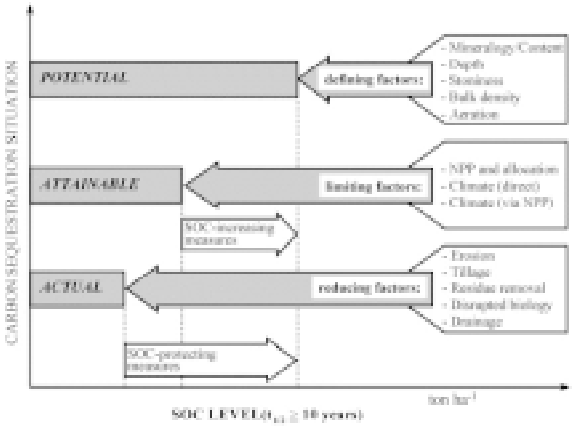
Source: Stewart (2007)

However, the proposed theory has few implications in soil carbon management because the true soil C saturation level may be of small practical importance, as large organic C inputs must be maintained over long time periods to sequester large quantities of C (Stewart *et al*., 2007). Because of the limitations placed on plant dry matter production and decomposition rates by climate and soil properties, there are specific levels of SOM that can be reached for any system in a particular geographical region and soil type. Hence, determining maximum attainable level of soil carbon under different agro-ecological regions of the country would be the pragmatic approach rather than determining carbon sequestration potential.

Carbon sequestration situations

Carbon storage and sequestration in agricultural soils is considered to be an important issue. In agro-ecosystem research, it is possible to differentiate three levels of crop production: *potential*, *attainable* and *actual* (Rabbinge and van Ittersum, 1994; van Ittersum and Rabbinge, 1997). Similarly, carbon sequestration in agricultural soils has also three situations *i.e.*, potential, attainable and actual. The amount of carbon present in the soil is the function of land use change, soil type, climate (rainfall and temperature) and management practices. This is due to:

- Clay content – physically protected= Potential C
- Climate – determines the net primary productivity = Attainable C
- Management practices = Actual C



(Adopted from Ingram and Fernandes, 2001)

Three terminologies are used in soil carbon sequestration study. They are $SOC_{potential}$, $SOC_{attainable}$ and SOC_{actual}. The term "carbon sequestration potential", in particular, is used with different meanings; sometimes referring to what might be possible given a certain set of management conditions with little regard to soil factors which fundamentally determine carbon storage. Regardless of its potential, the amount of carbon a soil can actually hold is limited by factors such as rainfall, temperature and sunlight, and can be reduced further due to factors such as low nutrient availability, weed growth and disease. The term "$Attainable_{max}$" is suggested as the preferred term for carbon sequestration in mineral soils, being more relevant to management than "potential" and thereby of greater practical value (Ingram and Fernandes, 2001). The attainable soil C sink capacity is only 50 to 66% of the potential capacity (Lal, 2004). $SOC_{potential}$ is the SOC level that could be achieved if there were no limitations on the system except soil type. Soil type has an influence because surfaces of clays and other minerals will influence how much organic C can be protected against decomposition. For a soil to actually attain $SOC_{potential}$, inputs of carbon from plant production must be sufficiently large to both fill the protective capacity of a soil and offset losses due to decomposition. Under dryland conditions (no irrigation) these factors will place a limit on the amount of residue that can be added to a soil such that attaining the $SOC_{potential}$ is not possible and a lower value is defined as $SOC_{attainable}$, results. The value of $SOC_{attainable}$ is the realistically best case scenario for any production system. To achieve $SOC_{attainable}$, no constraints to productivity (e.g., low nutrient availability, weed growth, disease, subsoil constraints, etc.) must be present. Such situations virtually never exist, and these constraints typically result in lower crop/pasture productivities than required to attain $SOC_{attainable}$. This second set of factors is referred to as reducing factors, which may well be under the control of farmers. Decreased productivity, induced by the reducing factors, leads to lower returns of organic carbon to soil and lower actual organic carbon contents (SOC_{actual}) (Badlock, 2008). It can be inferred that attainable level of organic carbon in Indian soils is generally limited by rainfall as we do not have much variation in mean annual temperature, although it may be limited in some areas and seasons. In this respect, use of simulation models like Roth-C, and DSSAT, Century could be useful tools to determine the attainable level of soil organic carbon under different agro-ecological regions of the country. Using models to predict changes in soil organic carbon under different scenarios can provide an idea of the effects of different land uses and management practices, such as stubble burning, grazing pressure and fertiliser use. Models are able to estimate likely changes in soil organic carbon under a range of conditions, across a range of spatial scales, and for much longer times than can be accommodated in experiments (Bruce *et al*., 2010).

Protection mechanisms of organic matter (OM) in soils

Mechanisms for C stabilization in soils have received much interest recently due to their relevance in the global C cycle. There are three main mechanisms for stabilization of OM in soil (Sollins *et al*., 2006). They are (i) Physical protection, (ii) Chemical stabilization or stabilization by organo-mineral bonding, and (iii) Biochemical stabilization. These three mechanisms basically involve the accessibility of OM to microbes and enzymes, interactions between the organic and mineral compounds and chemical resistance of organic molecules against microbial attack. If SOM is not protected by one of these mechanisms, it is considered as unprotected SOM.

1. Physical protection: SOM can be physically protected against microbial decomposition by soil aggregation. Aggregates physically protect SOM by forming physical barriers between microbes and enzymes and their substrates. The physical

protection exerted by macro- and/or micro-aggregates on POM-C is attributed to (i) the compartmentalization of substrate and microbial biomass and, (ii) the reduced diffusion of oxygen into macro-aggregates. The inaccessibility of substrate for microbes within aggregates is due to pore size exclusion and related to water filled porosity.

2. Chemical stabilization or stabilization by organo-mineral bonding: Chemical stabilization of SOM is due to the result of chemical and physico-chemical binding between SOM and soil minerals (i.e., clay and silt particles) (Six *et al*., 2002). In addition to the clay content, types of clay (i.e., 2:1 versus 1:1 versus allophanic clay minerals) influence the stabilization of SOM. Under identical annual OM input, a slower SOM turnover, a larger microbial biomass and more OM are expected in soils with a high clay content within the same climatic area (Müller and Höper, 2004).
3. Biochemical stabilization: It is the stabilization of SOM due to its own chemical composition (e.g., recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (e.g., condensation reactions) in soil. Humified OM, i.e., humic acids and humin in particular, represents the most persistent pool of SOM with mean residence times of several hundreds of years (Piccolo, 1996). With humification, plant residues are transformed into more stable forms (humus).

Carbon pools in agricultural soils

The active pool is assumed to be composed of microbial biomass and easily decomposable compounds (e.g., proteins and polysaccharides) from leaf litter and root-derived material with mean residence time (MRT) of few days to few years. The 'slow' or an intermediate pool is SOC pool that is consisting of structural plant residues and physically stabilized C, whose MRT varies from 10 to more than 100 years. The resistant or stable pool is considered to be composed of aliphatic compounds, often mineral stabilized, with MRT in the order of 1000 years (Trumbore, 1997; Paul *et al*., 2001; von Lützow *et al*., 2006). The carbon model predictive capacity depends on estimates of these carbon pools. A particular challenge for regional model applications is to derive estimates of soil carbon pools. Lal (2004) computed the soil carbon pool of major soil orders of India by taking into account the data of Velayuthum *et al*. (2000) and Eswaran *et al*. (1993, 1995).

Carbon stock of Indian soils

Lal *et al*. (2004) computed carbon sequestration potential of Indian soils by assuming converting degraded soils to restorative land use and estimated total potential of 39 to 49 (44 ± 5) Tg C y^{-1}. Indian soils have considerable potential of terrestrial/soil carbon sequestration. They estimated the soil organic carbon (SOC) pool of 21 Pg in 30 cm depth and 63 Pg in 150 cm depth. The restoration of wastelands, degraded/desertified soils and ecosystems (e.g., afforestation, improved pastures) and adoption of improved farm management practices can enhance soil organic carbon and improve soil quality and soil health. The organic carbon pool in soils of India and the world is presented in table 1 (adopted from Lal *et al*., 2004). All these estimates are based on Walkley and Black C measurement. However, there is problem of computing soil carbon stock by Walkley-Black method which gives only an approximation of soil organic carbon content. The Walkley-Black method gives variable recovery of soil organic C. A general standard conversion factor of 1.32 for incomplete oxidation of organic carbon is commonly used to convert Walkley-Black carbon to the total organic-C content, although true factors vary greatly between and within soils because of differences in the nature of organic matter in different soil depth and vegetation type.

Table 1 Organic carbon pool in soils of India and the world

Soil order	India		World	
	0–30 cm (Pg)	0–150 cm (Pg)	0–25 cm (Pg)	0–100 cm (Pg)
Alfisols	4.22	13.54	73	136
Andisols	–	–	38	69
Aridisols	7.67	20.3	57	110
Entisols	1.36	4.17	37	106
Histosols	–	–	26	390
Inceptisols	4.67	15.07	162	267
Mollisols	0.12	0.5	41	72
Oxisols	0.19	0.49	88	150
Spodosols	–	–	39	98
Ultisols	0.14	0.34	74	101
Vertisols	2.62	8.78	17	38
Total	20.99	63.19	652	1555

(Source: Adopted from Lal *et al*., 2004)

Strategies for soil carbon sequestration

The restoration of wastelands, degraded/desertified soils and ecosystems (e.g., afforestation, improved pastures) and adoption of improved farm management practices can enhance soil organic carbon and improve soil quality and soil health. Such management practices include organic agriculture, conservation tillage, mulching, cover crops, integrated nutrient management and agro-forestry, including improved management of pastures and rangelands (FAO, 2007).

Land use change

Restoration of degraded lands: A vast portion (120 m ha) of total geographical area of the country is affected by various forms of land degradation. It offers an opportunity for storing carbon in soil by adoption of land restorative processes. The total potential carbon sequestration through restoring degraded soils in India is 7 to 10 Tg C yr^{-1} (Lal, 2004). Some of the important measures for land restoration and carbon sequestration strategies are green manuring, mulch farming/conservation tillage, afforestation/agro-forestry, grazing management/ alley farming, integrated nutrient management/manuring, diverse cropping systems etc.

Erosion control: Accelerated soil erosion depletes the SOC pool severely and rapidly. Soil conservation and water management, water harvesting and recycling are important strategies of minimizing losses and restoring soil quality.

Soil and vegetation management

Residue management

Incorporating plant residues is one means by which we can add organic matter to soil. Removal of crop residues from field is known to hasten SOC decline especially when coupled with conventional tillage. Incorporation of crop residues favours immobilization because of wide C/N ratio in the crop residues.

The extent of residue or crop cover left on the soil surface depends on the availability. In our country, there are competing uses such as fuel, thatching material, feed for crop residues. Therefore, crop residues are mostly disposed off from crop fields. In some situations, where they are available in abundance, crop residues are considered as waste material and disposed-off by burning such as in the rice-wheat growing areas of north India.

Integrated nutrient management

Balanced application of inorganic fertilizers and organic amendments greatly influence accumulation of organic matter in soil and also influence the soil physical environment. Soil organic carbon (SOC) was significantly influenced by the fertilizer and organic manure applied over 28 years of cropping (Hati *et al*., 2007). The results showed that the soil organic carbon (SOC) content in 100% NPK and 100% NPK + FYM treatments increased by 22.5 and 56.3%, respectively over the initial level (1.14 kg m^{-2}). Application of fertilizers in combination with manure resulted in greater accumulation and build up of SOC. This is because SOC is directly related to organic inputs.

Improved cropping systems

Principal mechanism of SOC sequestration with conservation tillage is the increase in micro-aggregation and deep placement of SOC in the subsoil. Less tillage will influence the maintenance of C in un-decomposed residue and increase sequestered C in the soil. Incorporating plant residues adds organic matter to soil. Removal of crop residues coupled with conventional tillage lead to SOC decline. Crop rotations had significant influence on SOM content. Inclusion of legume in crop rotation resulted in build up of SOM. It is interesting to note that even in semi-arid areas where the cropping systems are mainly focused on water conservation, SOC improvements are noticed.

Modified land use systems

Alternate landuse systems like agroforestry system (AFS) has become an established approach to integrated land management, not only for renewable resource production, but also for ecological considerations. It represents the integration of agriculture and forestry to increase the productivity and sustainability of the farming system. Agroforestry (also known as multistrata tree gardens or analogue forests) and homegardens are other variants of these complex systems, but involve higher plant diversity. Trees play an important role in soil C sequestration (Takimoto *et al*., 2009); with an increase in the number of trees till complete stocking (high tree density) in a system, the overall biomass production per unit area of land will be higher, which in turn may promote more C storage in soils. In fact, recent research has reported higher soil C stock (amount of carbon stored in soil) under deeper soil profiles in agroforestry systems compared to treeless agricultural or pasture systems under similar ecological settings (Haile *et al*., 2008; Nair *et al*., 2009). Multipurpose trees (MPTs) form an integral component of different agroforestry interventions and models. MPTs, besides furnishing multiple outputs like fuel, fodder, timber, and other minor products, also help in the improvement of soil and other ecological conditions. Trees play various functions, including shading crops to reduce evapotranspiration, erosion control and nutrient cycling (Young, 1997). Some of the potential AFS are agri-horti-silviculture, multistoreyed AFS, home garden, agri-silviculture, horti-pastoral, Agri-horti-silvi-pastoral etc. Some of the other measures outlined by Lal (2008) are mentioned in table 2.

Table 2 Terrestrial carbon management options (Adopted from Lal, R. 2008)

Management of terrestrial C pool	Sequestration of C in terrestrial pool
Reducing emissions	*Sequestering emissions as SOC*
• eliminating ploughing	• increasing humification efficiency
• conserving water and decreasing irrigation need	• deep incorporation of SOC through establishing deep rooted plants, promoting bioturbation and transfer of DOC into the ground water
• using integrated pest management to minimize the use of pesticides	
• biological nitrogen fixation to reduce fertilizer use	• sequestering emissions as SIC
Offsetting emissions	• forming secondary carbonates through biogenic processes
• establishing biofuel plantations	• leaching of bicarbonates into the ground water
• biodigestion to produce CH_4 gas	
• bio-diesel and bioethanol production	
Enhancing use efficiency	
• precision farming	
• fertilizer placement and formulations	
• drip, sub-irrigation or furrow irrigation	

Biochar for soil carbon sequestration-An evolving approach

The use of biochar as soil amendments is proposed as a new approach for mitigating human induced climate change. Use of biochar in agriculture is not a new phenomenon; in primitive times farmers were using it for enhancing the production of agricultural crops. One such example is the slash and burn cultivation, which is still being practiced in some parts of north-eastern India. Pre-Columbian Amazonian natives are believed to have used biochar to enhance soil productivity and made it by smoldering agricultural waste. European settlers called it *Terra Preta de Indio*. Biochar can be used to sequester carbon on centurial or even millennial time scales. In the natural carbon cycle, plant matter decomposes rapidly after the plant dies, which emits CO_2; the overall natural cycle is carbon neutral. Instead of allowing the plant matter to decompose, pyrolysis can be used to sequester some of the carbon in a much more stable form. Biochar thus removes circulating CO_2 from the atmosphere and stores it in virtually permanent soil carbon pools, making it a carbon-negative process.

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Carbon Sequestration: Global and Indian Scenario

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Introduction

Coping with global warming and its consequences on climate are amongst the most serious challenges of the present century. Elevated concentration of greenhouse gases (GHGs) in the atmosphere is the strongest causal factor for global warming. The atmospheric concentration of CO_2 has increased from 280 ppm in 1750 to 367 ppm in 1999 and is currently increasing at a rate of 1.5 ppm or 3.3 Pg C yr^{-1} (IPCC, 2001). Similarly the atmospheric concentration of CH_4 has increased from 700 to 1745 ppb and that of N_2O has increased from 270 to 314 ppb during the same period. This anthropogenic increase of GHGs in the atmosphere and the cumulative radiative forcing of all GHGs has led to an increase in the global surface temperature of 0.6°C since 19th Century with the current warming rate of 0.17°C per decade (IPCC, 2001), which is higher than the critical rate of 0.1°C per decade. Since the industrial revolution, the global emissions of C are estimated as 270±30 Pg due to fossil fuel combustion and 136±55 Pg due to land use change and soil cultivation. Emissions due to land use change include those by deforestation, biomass burning, conversion of natural to agricultural system, drainage of wetlands and soil cultivation. There are three strategies of lowering CO_2 emissions to mitigate climate change (Schrag, 2007): (i) reducing the global energy use, (ii) developing low or no-carbon fuel, and (iii) sequestering CO_2 from point sources or atmosphere through natural and engineering techniques.

Most of the cultivated soils have lost half to two thirds of the original SOC pool with a cumulative loss of 30-40 Mg C ha^{-1}. Depletion of SOC pool has contributed to 78±12 Pg C to the atmosphere. The depletion of soil C is accentuated by soil degradation and mismanagement of soil. Adoption of recommended management practices (RMPs) on agricultural soils can enhance carbon sequestration and reduce the rate of enrichment of atmospheric CO_2 and will have positive impacts on food security, water quality and environment. Carbon sequestration is defined as the process of transfer and secure storage of atmospheric CO_2 into other long lived global pools including oceanic, pedologic, biotic and geological strata to reduce the net rate of increase in the atmospheric CO_2. Carbon sequestration may be a natural or anthropogenic driven process. The objective of an anthropogenic driven process is to balance global C budget such that future economic growth is based on a 'C-Neutral' strategy of no net gain in atmospheric C pool. A considerable part of the depleted SOC pool can be restored through conversion of marginal lands into restorative land uses, adoption of conservation tillage with cover crops, crop residue mulch, nutrient recycling, use of compost and efficient use of inputs in agriculture i.e., nutrient, water and energy. The natural rate of soil C sequestration through adoption of recommended management practices ranges from 50-1000 kg C ha^{-1} yr^{-1}. The cumulative C sequestration potential is 30-60 Pg over 25-50 year. The global potential SOC sequestration through these practices is 0.9±0.3 Pg C $year^{-1}$, which may offset one-fourth to one-third of the annual increase in atmospheric CO_2 estimated at 3.3 Pg C yr^{-1}. Besides mitigation of climate change, carbon sequestration builds soil fertility, improves soil quality, improves agronomic productivity, protect soil from compaction and nurture soil biodiversity.

Global carbon pools

There are five global C pools, of which the largest is the Oceanic pool which is estimated at 38000 Pg and is increasing at a rate of 2.3 Pg C yr^{-1}. The Geological C pool comprising fossil fuel estimated at 4130 Pg, is the second largest pool, of which 85% is coal, 5.5% is oil and 3.3% is gas (Fig 1). Presently, coal and oil each account for 40% of global CO_2 emissions (Schrag, 2007). Thus, the geological carbon pool is depleting through fossil fuel combustion at the rate of 7.0 Pg yr^{-1}. The third largest pool, is Pedologic pool estimated at 25000 Pg up to 1 m depth. It consists of two components: soil organic carbon (SOC) pool estimated at 1550 Pg soil and soil inorganic C pool (SIC) estimated at 950 Pg (Batjes, 1996). The SOC pool consists of highly active humus and relatively inert charcoal C. It comprises a mixture of (i) plant and animal residues at various stages of decomposition; (ii) substances synthesized microbiologically and/or chemically from the breakdown products; and (iii) the bodies of live micro-organisms and small animals and their decomposing products (Schnitzer, 1991). The soil inorganic carbon (SIC) pool includes elemental C and carbonates of minerals such as calcite, dolomite and gypsum and comprises primary and secondary carbonates. The fourth largest pool is the atmosphere comprising of 780 Pg of CO_2-C, and increasing at the rate of 3.5 Pg yr^{-1} or 0.46%. The smallest among the global pools is the Biota pool estimated at 560 Pg. The pedologic and the biotic pool together are called the 'Terrestrial C pool', estimated approximately 2860 Pg C. The terrestrial and atmospheric pools are strongly interacting with one another. The

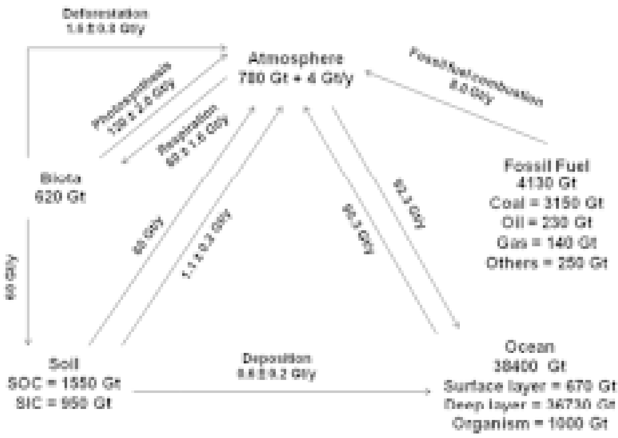

Fig 1 Pools and fluxes of soil carbon pool

annual rate of photosynthesis is 120 Pg C, whereas the respiration is 60 Pg C yr^{-1}. The terrestrial C pool is depleted by conversion from natural to managed ecosystem, extractive farming practices based on low external inputs and soil degrading land use. Among all the pools, C sequestration in the terrestrial pool is most economic and have no negative impact or threat on the ecosystem. The terrestrial sink is presently increasing at a rate of 2-4 Pg C yr^{-1} and it may increase to approximately 5 Pg C yr^{-1} by 2050.

The missing carbon

Despite the scientific certainty that the global carbon cycle is governed by the law of conservation, scientists are not being able to "balance" the storages and out flows. That is, after summing the flows of carbon to and from the atmosphere, that there is less carbon in the atmosphere than expected. During the 1990's, the atmosphere was missing about 3 peta grams (3 billion metric tons) of carbon per year. This missing carbon is associated with an unknown carbon sink. The unknown carbon sink is either an unknown mechanism that removes carbon from the atmosphere and/or a known mechanism that removes carbon faster than estimated by scientists.

Importance of carbon sequestration

Carbon sequestration builds soil fertility, improves soil quality, improves agronomic productivity, protect soil from compaction and nurture soil biodiversity. Increased organic matter in soil, improves soil aggregation which in turn improves soil aeration, soil water storage, reduces soil erosion, improves infiltration, and generally improves surface and groundwater quality. It is also helpful in the protection of streams, lakes, and rivers from sedimentation, runoff from agricultural fields, and enhanced wildlife habitat. Besides these, it has major roles in mitigating GHG gas emissions and in tackling the effects of climate change.

Principle behind the process of carbon sequestration

In terrestrial ecosystem, through the process of photosynthesis, plants assimilate 120 Gt C yr^{-1} and return 60 Gt C yr^{-1} to the atmosphere through respiration. The carbon that remains as plant tissue is then consumed by animals or added to the soil as litter when plants die and decompose. The primary way by which carbon is stored in the soil is as soil organic matter (SOM). SOM is a complex mixture of carbon compounds, consisting of decomposing plant and animal tissue, microbes (protozoa, nematodes, fungi, and bacteria), and carbon associated with soil minerals. Carbon can remain stored in soils for millennia, or be quickly released back into the atmosphere. Climatic conditions, natural vegetation, soil texture, and drainage, all affect the amount and length of time carbon is stored.

Soil aggregates enhance C sequestration by physically protecting it from the microbial activity (Gregorich *et al*., 1997). Current state-of-the-knowledge based on the existing models led to the concept that C sequestration is a function of the architectural system of soil aggregate packing. The SOC is first enmeshed in macroaggregates and then emerges as a dynamic nucleus for the formation of macroaggregates. The SOC is essential to the formation of macroaggregates because it is a primary source of energy for the microorganisms responsible for binding soil particles (Six *et al*., 1999). Macroaggregates promote greater storage of SOC than microaggregates (Puget *et al*., 1995), but this storage is transient (Sainju *et al*., 2003). Microaggregates, in contrast, promote long-term SOC sequestration, implying that the longivity of C sequestration would decrease with increasing aggregate size.

The position of SOC in the aggregates and its chemical nature affects the rate of its decomposition (Elliott *et al*., 1996; Christiansen, 1996; Besnard *et al*., 1996) and hence GHG emissions, which differ in the micro and macro aggregates. Organic matter of recent plant origin is believed to be preferentially recovered in sand size fraction (particulate organic matter), whereas more microbially processed material can be found in the silt and clay-size fraction (Chesire and Mundie, 1981). Camberdella and Elliott (1992, 1993) suggested that the labile organic pool within macro-aggregates of grassland soils is either particulate organic matter or relatively low density, mineral associated-organic matter, probably of microbial origin. On the other hand, the micro-aggregates are more resistant to microbial decomposition than that in macro-aggregates (Elliott, 1986). It was observed that C and N mineralization rates were greater in the macro-aggregates than in the micro-aggregates, and mineralization was enhanced when the macro-aggregates were crushed to the size of micro-aggregates (Elliott, 1986). Similar observations were also made by Aoyama *et al*. (1999), who reported that the amount of mineralized C in intact aggregates increased with the increase in the aggregate size irrespective of the agronomic treatments. However, there were no consistent trends for the N mineralization in relation to aggregate size. None the less, crushing the aggregates enhanced the mineralization of C by 14-35% and that of N by 17 to 103%. Thus, the SOM associated with the macro-aggregates was more labile and less processed than that associated with the micro-aggregates. Manna *et al*. (2005) reported that the C and N mineralization rate was greater in the macro-aggregates than in the micro-aggregates and was correlated significantly with the POM-C and POM-N, respectively in a long term fertilizer experiment. It was reported that the particulate organic matter is more sensitive to changes in management practices than the total organic matter (Camberdella and Elliott, 1992; Franzlubbers and Arshad, 1992; Chan, 1997; Bowman *et al*., 1999; Needelman *et al*., 1999). Chan (1997) reported that particulate organic matter was significantly correlated with macro-aggregate stability and mineralizable nitrogen. Wilson *et al*. (2001) also reported strong correlation between particulate organic matter and N mineralization under different farming systems with varying rotations, forms of tillage and cover crops.

The SOC sequestration in the soil is governed by the degree of physical, chemical, and physicochemical stabilization of SOM inside the aggregates (Fig 2). Aggregates physically protect SOM by forming physical barriers between microbes and enzymes and their substrate and controlling food web interactions and consequently microbial turnover. Chemical stabilization involves chemical or physicochemical binding between SOM and soil minerals

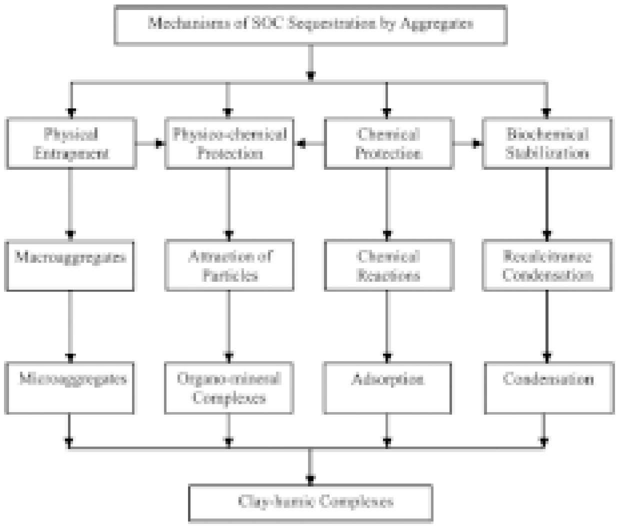

Fig 2 Pathways of soil organic carbon (SOC) sequestration by aggregates (Lal, 2004a)

(i.e., clay and silt particles, clay type). Biochemical stabilization involves stabilization of SOM due to its own chemical composition (e.g., recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (condensation reactions). Physicochemical interactive mechanisms define the maximum SOC sequestration capacity in a soil (Six *et al*., 2002). The encrustation of SOM in the center of microaggregates is the fundamental pathway to SOC sequestration (Tisdall and Oades, 1982; Golchin *et al*., 1994). This process of encrustation prevents organic matter from physical and chemical decomposition by microbial processes while sequestering SOC. The protected SOC pool stabilizes the microaggregates, while the microaggregates protect the SOC from microbial processes.

The SOM comprises a large and heterogeneous pool of C-enriched compounds. So the residence time of SOC in the organic pools ranges from a few minutes to hundreds of years. Residence times of relatively labile organic matter can be about 7 years in both silt and clay particles, whereas residence times for stable organics can reach 400 years in silt and 1000 years in clay (Buyanovsky *et al*., 1994). Residence times of SOC in macro- and microaggregates may differ because of (1) differences in physiochemical attraction between mineral and organic particles and (2) location of the organic binding agents within the aggregates (Emerson, 1959). The SOC residence time depends on the geo-chemical composition (Greenland, 1965), bonding agents (Tisdall and Oades, 1982), and size (Cambardella and Elliot, 1993; Six *et al*., 2000) of aggregates. Residence time of C increases with decreasing aggregate size. Losses of SOC from macroaggregates are faster and larger than those from microaggregates due to the differences in physical and chemical protection.

The SOC protection is proportional to the specific external surface area of the clay particles, and to the monolayer interfaces between clay and sand particles. Emerson (1959) found that organic matter unavailable to microbial processes is confined between the clay crystals. The stabilizing power of clay is high, thus clay soils contain more SOC than sandy soils. Montmorillonitic clays store and protect SOC more than illitic and kaolinitic clays because montmorillonites possess greater surface area, more interlayer spaces, and higher swell and shrink potential than illites and kaolinites. Montmorillonites protect SOC by preventing the microbes from accessing the C-rich organic substrates, by controlling microbial population, and by preserving the microbial metabolites (Wild, 1988).

Management options for enhancing C sequestration

The technological options for sequestration of atmospheric CO_2 into one of the global C pools can be broadly grouped into two categories: (i) abiotic and (ii) biotic sequestrations.

(a) Abiotic sequestration: It is based on physical and chemical reactions and engineering techniques without intervention of living organisms (e.g., plant and microbes). The abiotic strategy of C sequestration in oceanic and geological structures has received considerable attention (Freund and Ormerod, 1997) because theoretically abiotic sequestration has a larger sink capacity than biotic sequestration. It includes (i) Oceanic injection (ii) Geological injections (iii) Scrubbing and mineral carbonation.

(b) Biotic sequestration: It is based on management intervention of higher plants and micro-organisms in removing CO_2 from the atmosphere and also the anthropogenic interventions to reduce emissions or offset emissions. Increasing use efficiency of inputs (e.g., water, nutrient, energy) also contributes to increasing terrestrial C sequestration. The biotic sequestration includes C sequestration in oceans, forest ecosystem, wetlands and soil carbon sequestration.

Soil carbon sequestration implies removal of atmospheric CO_2 by plants and storage of fixed C as soil organic carbon. The strategy to enhance soil carbon sequestration involves increase of SOC density in soil, improve depth distribution of SOC and stabilizing SOC by encapsulating it within stable micro-aggregates so that C is protected from microbial processes or as recalcitrant C as humus with long turn over time. The management options for increasing SOC sequestration includes (i) conservation tillage (ii) cover crops (iii) efficient nutrient management (iv) efficient water management (v) restoring degraded soils (vi) practicing crop diversification and efficient cropping system (vii) minimizing soil and water erosion (viii) efficient pasture management (ix) afforestation and efficient forest management (x) efficient management of urban soils etc.

Different field practices, farm operations and agricultural inputs used in the process of crop production emits significant amount of CO_2 to the atmosphere (Lal, 2004b). Gifford (1984) has classified agricultural practices into primary, secondary and tertiary sources with reference to their C emission capacity. Primary sources of C emissions are either due to mobile operations (e.g., tillage, sowing, intercultural, harvesting and transport) or stationary operations (e.g., pumping water, grain drying, milling). Secondary sources of C emission comprise manufacturing, packaging and storing fertilizers and pesticides. Tertiary sources of C emission include acquisition of raw materials, fabrication of equipments and farm buildings etc. Therefore, reducing emissions implies enhancing use efficiency of all these inputs by decreasing losses, and using other C-efficient alternatives. Emissions of CO_2 from agriculture are generated from three sources: machinery used for cultivating the land, production and application of fertilizers and pesticides, and the SOC that is oxidized following soil disturbance (Lal, 2004b; West and Marland, 2002). More intensive land use might involve more fuel, farm machinery and agrochemicals and the production, packaging, transportation and application of these requires significant energy resources leading to an increase in GHG emissions (Vlek *et al*., 2003; Chauhan *et al*., 2005; Maraseni *et al*., 2010 a, b; Maraseni and Cockfield, 2011). Use of fertilizers and pesticides applied varies among crop types, crop rotations, and tillage practices. Lal (2004 b) reported that C emissions 2–20 kg CE ha^{-1} for different tillage operations, 1–1.4 kg CE ha^{-1} for spraying chemicals, 2–4 kg CE ha^{-1} for seeding and 6–12 kg CE ha^{-1} for combine harvesting. Similarly, estimates of C emissions in kg CE per kg for different fertilizer nutrients are 0.9–1.8 for N, 0.1–0.3 for P_2O_5, 0.1–0.2 for K_2O.

Impact of recommended management practices (RMPs) on carbon sequestration

Lal (2011) has suggested following recommended management practices over traditional practices in order to facilitate soil organic carbon sequestration. Therefore, conversion to restorative land uses (e.g., afforestation, improved pastures) and adoption of recommended management practices (RMP) can enhance SOC and improve soil quality. Important RMP for enhancing SOC include conservation tillage, mulch farming, cover crops, integrated nutrient management including use of manure and compost, and agroforestry.

Table 1 Comparison between traditional methods and recommended management practices

SN	Traditional methods	Recommended management practices (RMPs)
1.	Biomass burning and residue removal	Residue return as surface mulch
2.	Conventional tillage and clean cultivation	Conservation tillage, no till and mulch farming
3.	Bare/idle fallow during off-season	Growing cover crops during off-season
4.	Continuous monoculture	Crop rotations and diversification
5.	Low input subsistence farming and soil nutrient mining	Judicious use of off-farm input
6.	Intensive use of chemical fertilizers	Integrated nutrient management with compost, bio-solids and nutrient cycling, precision farming
7.	Intensive cropping	Integrated trees and livestock with crop production
8.	Surface flood irrigation	Drip, furrow or sub irrigation
9.	Indiscriminate use of pesticides	Integrated pest management
10.	Cultivating marginal soils	Conservation reserve programme, restoration of degraded soils through land use change

Agroforestry has importance as a carbon sequestration strategy because of carbon storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation. Proper design and management of agroforestry practices can make them effective carbon sinks (Montagnini and Nair, 2004; Bhadwal and

Singh, 2002) Average carbon storage by agroforestry practices has been estimated as 9, 21, 50, and 63 Mg C ha^{-1} in semiarid, subhumid, humid, and temperate regions, respectively. For smallholder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C ha^{-1} yr^{-1}(Montagnini and Nair, 2004). Another indirect avenue of C sequestration is through the use of agroforestry technologies for soil conservation, which could enhance C storage in trees and soils. Agroforestry systems with perennial crops may be important carbon sinks. Lal (2004a) reported that permanent pasture has the highest C sequestration potential (Table 2).

Table 2 Estimates of global soil carbon sequestration potential

Sr. No.	Land use	Soil carbon sequestration potential (Pg C $year^{-1}$)	Reference
1.	World cropland	0.43-0.57	Lal and Bruce (1999)
2.	Desertification control	1.0	Squires *et al.* (1995)
3.	Desertification control	0.2-0.4	Lal (2001)
4.	Soils of tropics	0.28- 0.54	Lal (2002)
5.	World soil	0.4-0.8	IPCC (1996)
6.	Permanent pasture	1.87	Conant *et al*. (2001)

Conservation tillage and carbon sequestration

Several studies compare soil organic carbon (SOC) in conventional and conservation tillage (CT) systems. Tillage generally disrupts aggregation and exposes particulate organic matters (POM) which decompose quickly by microbial action. Reduced C sequestration in CT compared to no tillage (NT) is due to differences in aggregates and aggregate associated carbon. Study revealed that concentration of fine iPOM (intra aggregate POM) was less in CT compared in NT macro aggregates. On a whole soil basis, fine iPOM C was 51% less in CT than NT and accounted for 21% total carbon difference between NT and CT. The concentration of free light fraction (LF) was not affected by tillage but was on an average 45% less in CT than native vegetation (Six *et al*., 1999). The results from analysis suggest that switching from conventional cultivation to zero till would clearly reduce on-farm emissions. VandenBygaart *et al*. (2003) found that reduced tillage increases the amount of carbon sequestered by an average of 320-150 kg C ha^{-1} in 35 studies of western canada and that the removal of fallow enhanced soil carbon storage by 150-160 kg C ha^{-1} based on 19 studies. West and Marland (2002) reported that carbon emission from conventional tillage (CT), reduced tillage (RT) and no tillage (NT) were 72.02, 45.27, 23.26 kg C ha^{-1}, respectively in case of corn cultivation and 67.45, 40.70, 23.26 kg C ha^{-1}, respectively, for soyabean cultivation based on annual fossil fuel consumption and CO_2 emission from agricultural machinery. Thus, there was 67.70% and 65.41% reduction in CO_2 emission as compared to conventional tillage, for corn and soyabean cultivation, respectively. West and Marland (2002) reported that no-till emitted less CO_2 from agricultural operations than did conventional tillage and estimated that net relative C flux, following a change from CT to NT on non-irrigated crops was -368 kg C ha^{-1}. Mosier *et al*. (2006) reported that based on soil C sequestration, only NT soils were net sinks for Global Warming Potential (GWP). Thus, economic viability and environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer. Ghosh *et al*. (2010) reported that double no-till practice in rice-based system is cost-effective, restored soil organic carbon (70.75%), favoured biological activity (46.7%), conserved water and produced yield higher (49%) than conventional tillage.

Table 3 Average net carbon flux for US with changes in tillage practices

	Conventional tillage (kg C $ha^{-1}yr^{-1}$)	No-tillage (kg C $ha^{-1}yr^{-1}$)
C Sequestration in soil	0	- 337
C emission from farm machinery	+ 69	+ 23
C emissions from agril. inputs	+ 99	+ 114
Net C flux	+ 168	- 200
Relative net C flux	0	- 368

West and Marland (2002) estimated the average net C flux for U.S. at +168 kg C ha^{-1} yr^{-1}, when continuing CT practices. The net C flux following a change from CT to NT was -200 kg C $ha^{-1}yr^{-1}$. Thus, the total change in the flux of CO_2 to the atmosphere, following a change from CT to NT on non-irrigated crops, was expected to be about -368 kg C $ha^{-1}yr^{-1}$ (Table 3).

Impact of tillage and crop rotations on carbon sequestration

Results from several field experiments under various climatic conditions revealed that crop rotations, in combination with tillage, sequestered more soil carbon (Yang and Kay, 2001; Sainju *et al*., 2006; Campbell *et al*., 1995). Meyer-Aurich *et al*. (2006) conducted an experiment with two levels of tillage and eight different corn-based crop rotations. They found that continuous alfalfa rotation had the highest sequestration rates (513 kg C ha^{-1} yr^{-1}). Carbon storage of soils in the corn–corn–alfalfa–alfalfa rotation was significantly higher than in the corn–corn–soybean–soybean rotation. Rotations which included cereals and red clover, had soil carbon levels that were between those observed for continuous alfalfa and corn–corn–soybean–soybean rotation. Crop rotation is very effective in carbon sequestration than continuous cultivation of single crop every year. Mandal *et al*. (2007) reported that rice-mustard-sesame registered significantly higher rate of carbon sequestration (1.91 Mg C ha^{-1} yr^{-1}) than that of rice-fallow-rice (0.28 Mg C ha^{-1} yr^{-1}) and rice-wheat-fallow (0.27 Mg C ha^{-1} yr^{-1}) system. Inclusion of crops which leave behind higher amount of crop residues and/or root carbon facilitate higher SOC sequestration. They observed that besides quantity, the quality of residue also decide the rate of SOC sequestration. The residues with wider C:N ratio (rice and wheat) facilitate higher SOC sequestration than residues with narrower C:N ratio (jute, berseem etc.).

Cropping and pasture systems were compared for soil organic C in Georgia. Soil organic C was greater near the soil surface under pasture than under conservation-tilled cropland, which was greater than that under conventional-tilled crop land. In several field experiments, crop rotation including legume crops were found to be more beneficial for carbon sequestration. Crop rotations along with conventional tillage increases the rate of carbon sequestration, and with conservation tillage the rate is much higher than earlier (Gaisera *et al.,* 2009). Franzlubbers (2010) reported greater soil organic C accumulation under pastures than under annual crops which was due to longer growing periods, more extensive root system, and less soil disturbance.

Impact of tillage and crop residues on carbon sequestration

The impact of conservation tillage and crop residues incorporation have shown remarkable potential in C sequestration as compared to conservation tillage alone. Conservation agriculture using crop residue as mulch and no till farming can sequester more SOC through conserving water, reducing soil erosion, improving soil structure, enhancing SOC concentration, and reducing the rate of enrichment of atmospheric CO_2 (Lal, 2004a). Doraiswamy *et al.* (2007) reported that ridge tillage in combination with fertilizer and crop residue is very effective in SOC sequestration through erosion control. Ghimire *et al*. (2008) reported that SOC sequestration could be increased with minimum tillage and surface application of crop residue and SOC sequestration was highest in top 0-5 cm soil depth irrespective of the tillage and crop residue management practices. Suman *et al*. (2009) reported that changes in residue management and incorporation of organic manures may help in carbon sequestration by restoring soil organic carbon (SOC).

Ghimire *et al*. (2008) reported that soil (0-50 cm depth) retained 8.24 kg C m^{-3} under no-tillage practice, which was significantly higher than conventional tillage treatment (7.86 kg C $m^{-3)}$. Crop residue treatment in no-tillage soils sequestered significantly higher amount of SOC than any other treatments in the top 15 cm soil depths. Thus, it was revealed that SOC sequestration could be increased with minimum tillage and surface application of crop residue. Crop residue served as a source of carbon for these soils especially in upper soil depths. No-tillage practice minimizes exposure of SOC to oxidation, ensuring higher SOC sequestration in surface soils of no-tillage with crop residue application.

Impact of efficient use of nutrients and water on carbon sequestration

It is interesting to note that efficient management of inputs leads to carbon sequestration that helps in increasing the agricultural inputs use efficiency. Sequestration of soil organic carbon helps in improving the physical, chemical and biological health of soil. The agricultural inputs include water, nutrient, energy and agrochemicals. There is continuous decline in the factor productivity of these inputs due to their inefficient use and deterioration of soil health.

Efficient use of these inputs helps in reducing the cost of cultivation, sustaining agricultural productivity at higher level with minimal environmental pollution.

(a) Nutrient management

Judicious nutrient management is crucial to SOC sequestration. Use of organic manures and compost enhances the SOC pool more than application of the same amount of nutrients as inorganic fertilizers (Gregorich *et al*., 2001). The fertilizer effects on SOC pool are related to the amount of biomass C produced/returned to the soil and its humification. Adequate supply of N and other essential nutrients in soil can enhance biomass production under elevated CO_2 concentration (Van Kessel *et al*., 2000). Long-term manure applications increase the SOC pool and may improve aggregation (Sommerfeldt *et al*., 1988; Gilley and Risse, 2000), and the effects may persist for a century or longer (Compton and Boone, 2000). Potential of conservation tillage to sequester SOC is greatly enhanced where soils are amended with organic manures (Hao *et al*., 2002). Smith and Powlson (2000) estimated that if all the manure produced in Europe were incorporated into arable land in the European Union, there would be a net sequestration of 6.8 Tg C yr^{-1}, which is equivalent to 0.8% of the 1990 CO_2-C emissions for the region. Beneficial impacts of manuring for U.S. cropland were reported by Lal *et al*. (1998). There are certain hidden carbon costs involved with the manufacture and use of agricultural inputs (Lal *et al*., 2004 b). It has been reported that carbon equivalent (CE) emission per kg of different fertilizer nutrients are 0.9-1.8 kg for N, 0.1-0.3 kg for P_2O_5, 0.1-0.2 kg for K_2O and 0.03-0.23 kg for lime. Estimates of C emissions in kg CE per kg active ingredient of different pesticides are 6.3 for herbicides, 5.1 for insecticides and 3.9 for fungicides. Pathak *et al*. (2011) reported that the NPK+FYM treatment sequestered 0.33 Mg C ha^{-1} yr^{-1}, whereas the NPK treatment sequestered 0.16 Mg C ha^{-1} yr^{-1} compared to the control treatment. The carbon sequestration potential in different nutrient management scenarios of the long term fertilizer management (LTFE) treatments of India ranged from 2.1 to 4.8 Mg C ha^{-1}during the study period (average 16.9 yr^{-1}). In 17 out of 26 LTFEs, the NPK+FYM treatment had higher SOC and also higher net return than that of the NPK treatment. In the remaining 9 LTFEs, SOC sequestration in the NPK+FYM treatment was accomplished with decreased net return suggesting that these are economically not attractive and farmers have to incur additional cost to achieve C sequestration.

(b) Irrigation

Similar to the addition of fertilizers and manures in a nutrient-depleted soil, judicious application of irrigation water in a drought prone soil can enhance biomass production, increase the amount of above ground and the root biomass return to the soil and improve SOC concentration. Enhancing irrigation efficiency can also decrease the hidden C cost (Sauerbeck, 2001). In Texas, Bordovsky *et al*. (1999) observed that the surface SOC concentration in plots growing irrigated grain sorghum and wheat increased with time. Irrigation can also enhance SOC concentrations in grassland (Conant *et al*., 2001).

Modeling carbon sequestration

The use of process based models has opened a new era of assessing the SOC stock and its change due to climatic and land management practices with considerable accuracy. These models also give the option of choosing the land use practices for maintaining soil health and combating climate change through C sequestration. Smith *et al*. (1997) showed that the soil organic carbon models can be grouped into two groups in terms of overall performance. Performance of the group containing SOMM, ITE and Verberne was poorer than the group containing RothC, CANDY, DNDC, CENTURY, DAISY and NCSOIL. Some of these differences could be ascribed to the level of site-specific calibration used – some models took advantage of this, while others could not. The other main factor was that all of the models in the poor performing group were less developed for land-use systems other than that for which they were developed in the first place. ITE and SOMM, for example, are forestry/grassland models and attempted to simulate arable crops assuming they were grasses. These two models performed better on forestry datasets, but interestingly, no better than other more generally applicable models. The performance of the CENTURY model was evaluated by Bhattacharya *et al.* (2007) with two long term datasets of India. It was found that the model performed better in Ludhiana than in the Barrackpore dataset. Recently, integration of SOM models with GIS based database provides a potential tool for identification of national greenhouse inventories which are important for C trading. Evolution of the model will continue with the improvement in our understanding of biogeochemical processes. The identification of problem areas where processes are not adequately quantified is key to further developments.

Constraints in soil carbon sequestration

There are several constraints for soil carbon sequestration which should be taken into consideration while designing any carbon sequestration strategies.

- In the tropics and subtropics the climate is harsh and the resource poor farmers can not afford the off-farm inputs.
- There are biophysical constraints on agricultural production.
- SOC sequestration requires input of crop residues/biosolids and fertilizers/manures to enhance biomass production. However there is alternate competing demands of these inputs.
- Hidden carbon costs are involved with the agricultural inputs.
- The rate of mineralization is high and the rate of humification is low in the tropics.
- There is finite sink capacity of the SOC pool.

Conclusions

In a nutshell it may be concluded that

- Sequestering carbon in soil and biota can mitigate climate change.

- Recommended management practices like conservation tillage, crop rotation, residue management and integrated nutrient management have good potential in improving soil carbon sequestration.
- Efficient use of agricultural inputs would reduce greenhouse gas emissions and result in carbon sequestration.
- Sequestration of carbon in soil can improve soil health which will help in improving input use efficiency in agriculture
- Site specific technologies should be developed and disseminated for improving carbon sequestration and enhancing input use efficiency.
- Remote sensing, GIS and Simulation model can serve as useful tools in estimation and prediction of carbon sequestration at regional scale.

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Soil Carbon Sequestration and its Potential in Mitigating Climate Change

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Introduction

Warming of the climate system is an established fact, which is evident from the increase in global average air and ocean temperatures, widespread melting of snow and ice and rising average global sea level. The warming trend in India over the past 100 years (1901 to 2007) was observed to be 0.51^{0}C with accelerated warming of 0.21^{o}C per every 10 years since 1970. Global green house gas (GHG) emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 whereas the emission of carbon dioxide (CO_2) has grown by about 80% between 1970 and 2004, from 21 to 38 gigatonnes (Gt), and represented 77% of total anthropogenic GHG emissions in 2004 (IPCC, 2007). With the current climate change mitigation policies, global GHG emissions will continue to grow over the next few decades. A warming of about 0.2°C per decade is projected for a range of emissions scenarios for the next two decades. Even if the concentrations of all GHGs and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected (IPCC, 2007). Analysis at one hundred twenty five years data in India revealed that climate change impacts on agriculture are being witnessed all over the world, but countries like India are more vulnerable in view of the high population depending on agriculture and excessive pressure on natural resources. The projected impacts are likely to further aggravate yield fluctuations of many crops with impact on food security and prices. By 2100, cereal productivity is projected to decrease by 10-40% and greater loss is expected in *rabi*. There are already evidences of negative impacts on yield of wheat and paddy in parts of India due to increased temperature, increasing water stress and reduction in number of rainy days. Water requirement of crops is also likely to go up with projected warming and extreme events are likely to increase. In view of the widespread influence of climate change, there is a need to reduce the emissions of green house gases which are the main drivers of climate change. The mean annual temperature increase was more rapid in recent years than last century (Fig 1) (AICRPAM, 2010-11).

Declining per capita availability of natural resources due to population growth, urbanization, industrialization, competing environmental demands and all inclusive growth are major concerns of resource management and conservation. India has only 2.5% of the

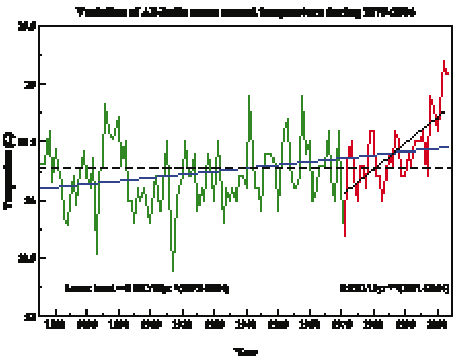

Fig 1 Trends in mean annual temperatures in India during 125 years

total geographical area of the world supporting 17% of the global population. Its population increased from 361 million in 1951 to 1140 million at present, a three-fold increase in a span of little over 50 years. As of today, there is food sufficiency in the country, but by 2020, India needs about 300 million tones of food grains. The production in 2008-2009 was only 230 million tones, implying that about 70 million tones of food grains have to be produced from the same or lesser land, resulting in higher stress on soil system. Most of the intensive productions systems in India are showing a yield plateau, and crop response to inputs is declining. It means that for each additional kg of yield, more and more nutrients are needed. This has negative economic as well as ecological implications in terms of low nutrient use efficiency, lesser biomass production per unit input and increased emission of green house gasses like CO_2 and nitrous oxides.

Emissions of GHGs from agriculture in India

Agriculture sector is one of the main sources of GHG emissions throughout the world and in India as well. In India, agriculture contributed about 17% of the CO_2 equivalent emissions for the base year 2007 (INCCA, 2010). Details of GHG emissions from agriculture are given below:

a) **CH_4:** The agriculture sector dominates the total national CH_4 emissions, within which emissions due to enteric fermentation (63%) and rice cultivation (21%) are the largest. Methane emissions from various categories of animals range from 28 to 43 g CH_4/ animal. The methane emission coefficient for continuously flooded rice fields is about 17 g/ m^2. Burning of crop residue is a significant net source of CH_4 in addition to other trace gases.

b) **N_2O:** Agriculture sector accounted for 71 percent of total N_2O emission from India in 2007. Emissions from soils are the largest source of N_2O in India followed by manure management. Emissions of N_2O results from anthropogenic nitrogen input through direct and indirect pathways, including the volatilization losses from synthetic fertilizers and animal manure application, leaching and run-off from applied nitrogen to aquatic systems.

c) **CO_2:** CO_2 emissions from agriculture are due to the consumption of diesel for various farm operations and due to the use of electricity for pumping of groundwater. Land use conversion from forests to agriculture due to shifting cultivation and on-site burning also results in CO_2 emissions.

The U.N. Framework Convention on Climate Change (UNFCCC) proposed a treaty in December, 1997 in Kyoto, Japan to make it mandatory for industrialized nations to reduce their fossil fuel emission by 5 per cent below the 1990 level. Subsequently, the Kyoto Protocol was revised in Bonn in July, 2001 and two new clauses relevant to SOC sequestration allowing countries to subtract from their industrial C emissions with C sequestered in 'sinks' such as forests and soils and to trade emission allowances that can reduce abatement costs (Lal, 2004). The UNFCCC Kyoto Protocol recognizes soil C sinks provided that the rate of SOC sequestration and the cumulative magnitude can be verified by standard procedures.

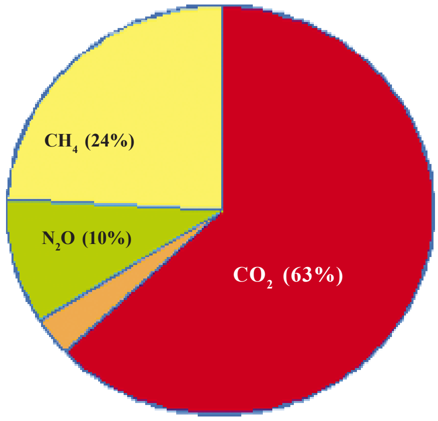

Fig 2 Major GHGs in Indian Agriculture

Increase in greenhouse gases (GHG) in the atmosphere and the resulting climatic change will have major effects in the 21st century. It is essential that a number of actions be undertaken in order to reduce GHG emissions and to increase their sequestration in soils and biomass. In this connection, new strategies and appropriate policies for agricultural and forestry management must be developed. One of the options is concerned with carbon sequestration in soils or in terrestrial biomass, especially on land used for agriculture or forestry. It is important to identify and implement policy instruments that facilitate realization of this sink. The SOC sequestration may also be credited under the Clean Development Mechanism (CDM, Article 12), Emission Trading (Article 17) or Joint Implementation Activities (Article 6) of the Kyoto Protocol (Lal, 2004). This will have significant effects on soil properties and a positive impact on land management environment. The consequences could improve soil fertility status and land productivity for food production and food security.

The most important reason for declining yield trends of various production systems in India is degraded soil health. Most of the agro ecological regions are showing reduction in organic carbon with continuous cropping with improper crop management practices such as low biomass recycling, inappropriate tillage methods, harvest and removal of every small component of biological produce and virtually no return of any plant residue back to the soil, burning of the residues in the field itself for preparation of clean seed bed, open grazing etc, that aggravate the process of soil degradation (Srinivasarao *et al*., 2012 a, b). As a result of several above mentioned reasons, soils encounter diverse constraints broadly on account of physical, chemical and biological soil health and ultimately end up with poor functional capacity. The first predominant cause of soil degradation in rainfed regions is water erosion. The process of erosion sweeps away the topsoil along with organic matter and exposes the subsurface horizons. The second major indirect cause of degradation is loss of organic matter by temperature mediated rapid decomposition of organic matter leading to rapid loss of soil fertility. If one looks at the tenth five year plan document of the Government of India, under chapter 5.1(5.1.72-74) on agriculture, it has been stated that, a sizeable quantity of organic farm waste is generated which could be utilized for providing nutrition to the crops after converting it into compost or manure.

Carbon sequestration potential and challenges

Soil carbon has gained increased interest in the recent past owing to its importance in carbon sequestration studies and its potential impact on sustainable crop production. Carbon sequestration implies removing atmosphere carbon and storing it in natural reservoirs for extended periods (Lal, 2011). Soil carbon sequestration is the process of transferring carbon dioxide from the atmosphere into the soil through crop residues and other organic solids, and in a form that is not immediately emitted. This transfer or "sequestering" of carbon helps to off-set emissions from fossil fuel combustion and other carbon-emitting activities while enhancing soil quality and long-term agronomic productivity. However, accuracy in estimating soil carbon sequestration to determine best management practices is hindered by inherent variability of soil properties (Srinivasarao *et al*., 2008, 2009b).

Maintaining or arresting the decline in soil organic matter (SOM) is the most potent weapon in fighting against soil degradation and for ensuring sustainability of agriculture in tropical regions. In India nearly 60 per cent of agriculture is rainfed, covering the categories of arid, semi-arid and sub-humid climatic zones. Consequences of depletion of organic matter are poor soil physical health, loss of favorable biology and occurrence of multiple nutrient deficiencies. In the rainfed arid, semi-arid and sub-humid tracts, apart from poor rain water management, depletion of nutrients caused by organic matter deficiency is one of the important causes of soil degradation. Improving organic matter is, therefore, crucial to sustenance of soil quality and future agricultural productivity. Humus is known to favor many useful physical, chemical and biological processes that occur within the soil (Srinivasarao *et al*., 2011c). Accordingly, soil organic matter is the key element of soil management that prevents erosion and improves water availability. Other soil physical characteristics that are linked to soil organic matter are: infiltration, water retention, bulk density and soil strength. When spread on the surface as mulch, organic matter moderates the bomb-like effect of falling rain drops and prevents dispersion-mediated erosion, surface crusting, and hard setting.

Soil carbon stocks

Soil carbon sequestration is yet another strategy towards mitigation of climate change. Soil carbon pool plays a crucial role in the soil's quality, availability of plant nutrients, environmental functions and global carbon cycle. Agricultural soils are among the earth's largest terrestrial reservoirs of carbon and hold potential for expanded carbon sequestration. They provide a prospective way for reducing atmospheric concentration of CO_2. Drylands are generally low in fertility, low in organic matter, and hence candidates for carbon sequestration (Srinivasarao *et al.,* 2003; 2012a). Carbon storage in the soil profile not only improves fertility but also abates global warming. Several soils, production and management factors influence carbon sequestration; and it is important to identify production and management factors that enhance carbon sequestrations in dryland soils. The objective of the present study was to examine carbon stocks at twenty-one sites under on going rainfed production systems and management regimes since the last 25 years on dominant soil types, covering a range of climatic conditions in India. Organic carbon stocks in the soil profiles across the country showed wide variations and followed the order Vertisols>Inceptisols>Alfisols>Aridisols. Inorganic carbon and total C stocks were larger in Vertisols than in other soil types. Soil organic carbon stocks decreased with depth in the profile, while inorganic carbon stocks increased with depth. Among the production systems, soybean, maize and groundnut based systems showed higher organic carbon stocks than other production systems. However, the highest contribution of organic carbon to total carbon stock was under upland rice system. Organic carbon stocks in surface layer of the soils increased with rainfall (r=0.59*) while inorganic carbon stocks in soils were found in the regions with less than 550 mm annual rainfall. CEC showed better correlation with organic carbon stocks than clay content in soils. Results suggest that Indian dryland soils are low in organic carbon but have potential to sequester. Further potential of tropical soils to sequester more C in soil could be harnessed by identifying appropriate production systems and management practices for sustainable development and improved livelihoods in the tropics (Srinivasarao *et al*., 2009b, c).

In general, SOC stocks increased as the mean annual rainfall increased. Significant correlation ($p< 0.05$) was obtained between SOC stock and mean annual rainfall ($r=0.59^*$, Fig 3). On the other hand, soil inorganic carbon (SIC) stocks decreased from 156.4 Mg ha^{-1} to 25.97 Mg ha^{-1} with the increase in mean annual rainfall from <550 mm to >1100 mm. As the SIC stocks were more dominant than SOC, total carbon stocks decreased from 183.79 Mg ha^{-1} with increase in mean annual rainfall from <550 mm to >1100 mm in the arid environment 70.24 Mg ha^{-1} in sub-humid regions. However, CEC showed significant positive

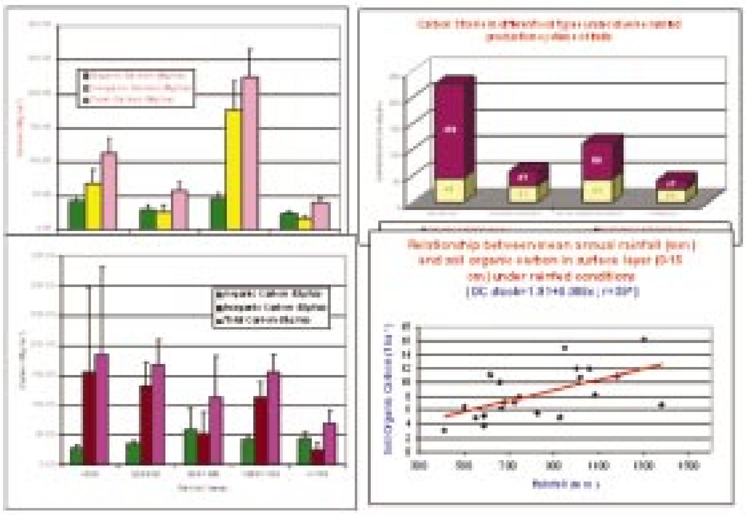

Fig. 3 Carbon stocks in diverse soil types and rainfall zones

(Srinivasarao *et al*., 2006, 2009b, 2011b) correlation (r=0.81**) while clay content in soil showed non-significant positive correlation with organic carbon stocks. This indirectly indicates that the type of clay mineral with larger surface area is largely responsible for higher carbon sequestration (Figure 3 and 4).

It has been postulated that aridity in the climate is responsible for the formation of pedogenic calcium carbonate and this is a reverse process to the enhancement in soil organic carbon. Thus, increase in C sequestration via soil organic carbon enhancement in the soil would induce dissolution of native calcium carbonate and the leaching of SIC would also result in carbon sequestration (Sahrawat, 2003). In the present scenario of differing climatic parameters such as temperature and annual rainfall in some areas of the country, it will continue to remain as a potential threat for carbon sequestration in tropical soils of the Indian sub-continent. Therefore, the arid climate will continue to remain as a bane for Indian agriculture because this will cause soil degradation in terms of depletion of organic carbon and formation of pedogenic $CaCO_3$ with the concomitant development of sodicity and / or salinity (Eswaran *et al*., 1993).

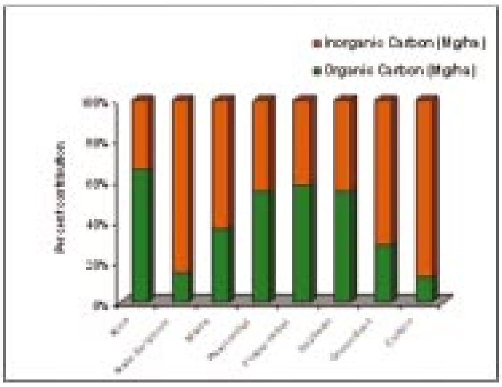

Fig 4 Distribution of organic and inorganic carbon in diverse rainfed production systems of India (Srinivasarao *et al*., 2009b)

Although, tropical regions have limitation of sequestering carbon in soil due to high temperature, adoption of appropriate management practices helps in sequestering reasonable quantities of carbon in some cropping systems particularly in high rainfall regions (Srinivasarao *et al*., 2009, 2011b, 2012 b). The potential of cropping systems can be divided in to that of soil carbon sequestration and sequestration in to vegetation. Tree based systems can sequester substantial quantities of carbon in to biomass in a short period. Total potential of soil C sequestration in India is 39 to 49 Tg yr^{-1} (Lal, 2004). This is inclusive of the potential of the restoration of degraded soils and ecosystems which is estimated at 7 to 10 Tg C yr^{-1} (Table 2). The potential of adoption of recommended package of practices on agricultural soils 6 to 7 Tg yr^{-1}. In addition, there is also a potential of soil inorganic carbon sequestration estimated at 21.8 to 25.6 TgC yr^{-1}. Long term manurial trials conducted in arid regions of Andhra Pradesh (at Anantapur) under rainfed conditions indicate that the rate of carbon sequestration in groundnut production system varied from 0.08 to 0.45 t ha^{-1} $year^{-1}$ with different nutrient management systems (Srinivasarao *et al*., 2009). Under semi arid conditions in alfisol region of Karnataka, the rate of carbon sequestration was 0.04 to 0.38 t ha^{-1} $year^{-1}$ in finger millet system under diverse management practices. Under rabi sorghum production system in vertisol region of Maharashtra (semi arid), the sequestration rate ranged from 0.1 to 0.29 t ha^{-1} yr^{-1} with different integrated management options. In soybean production system in black soils of Madhya Pradesh (semi arid), the potential rate of carbon sequestration is up to 0.33 t ha^{-1} yr^{-1} in top 20 cm soil depth.

Recent studies on changes of carbon in soils of SAT have shown that over a period of nearly 25 years, SOC stock has increased from 34 to118%. This has been possible due to adoption of the management interventions. Thus, appropriate management interventions in maintaining the capability of productive soils and also to raise the productivity of less productive soils are capable of enhancing organic carbon storage capacity of Indian soils. The sink capacity of SOM for atmospheric CO_2 can be greatly enhanced when degraded soils and ecosystems are restored, marginal agricultural soils are converted to a restorative land use or replaced to perennial vegetation and Recommended management Practices (RMPs) adopted in agricultural soils (Table 1) (Lal, 1997, 2009). Soil carbon sequestration potential by restoring degraded soils is presented in Table 2.

Table 1 Comparison between traditional and recommended management practices in relation to soil organic carbon sequestration

S. No.	Traditional methods	Recommended Management Practices (RMPs)
1	Biomass burning and residue removal	Recycling of residues
2.	Conventional tillage and clean cultivation	Conservation tillage, no till and mulch farming
3	Bare/idle fallow	Growing cover crops during off season preferably legumes
4	Continuous monoculture	Crop rotation with high diversity
5	Low input subsistence farming and soil nutrient fertility mining	Judicious use of farm inputs
6	Intensive use of chemical fertilisers	Integrated nutrient management with compost, bio-solids and nutrient recycling, precision farming
7	Intensive cropping	Agro-Forestry, wherever feasible
8	Surface flood irrigation	Drip, furrow or sub-irrigation
9	Indiscriminate use of pesticides	Integrated pest management
10	Cultivating marginal soils	Conservation reserve program. Restoration of degraded soils through land use change

(Source: Lal, 2004)

Reduce Soil Erosion

Although India receives relatively high rainfall, there is large temporal and spatial variation. Unlike temperate countries, rainfall occurs in high intensity storms carrying away top soil through runoff. Because of the skewed distribution of the rainfall, crops invariably experience water stress. Therefore, soil and water conservation and harvesting of surplus runoff are of paramount importance. The total water received through annual precipitation in India is estimated at 400 m ha m. About 300 m ha m is received during June to September, while another 100 m ha m during the rest of the year. About 20 m ha m of runoff is brought from outside India, thus making a total of 420 m ha m of water resource for use. The cardinal principles of soil and water conservation are: (i) conserve rainfall by reducing runoff losses

Table 2 Soil organic carbon sequestration potential through restoration of degraded soils

Degradation process	Area (M ha)	SOC sequestration rate (kg ha^{-1} y^{-1})	Total SOC sequestration potential (Tg C y^{-1})
Water erosion	32.8	80-120	2.62-3.94
Wind erosion	10.8	40-60	0.43-0.65
Soil fertility decline	29.4	120-150	3.53-4.41
Waterlogging	3.1	40-60	0.12-0.19
Salinization	4.1	120-150	0.49-0.62
Lowering of water table	0.2	40-60	0.01-0.012
Total			7.20-9.82

and by storing as much as possible in the profile and, (ii) adopt farm practices to make the most efficient use of the soil moisture by crops. In the beginning, machenical structures like bunding are emphasized, but more recently the focus shifted to field- and community-based *insitu* conservation practices. The main aim of these practices is to reduce or prevent water erosion or wind erosion, while providing the desired moisture for crop production. Based on past experiences, several field based soil and water conservation measures have been found promising for various rainfall zones in India (Table 3).

Table 3 Recommended soil and water conservation measures for various rainfall zones in India

Seasonal rainfall (mm)

<500	500-700	750-1000	>1000
• Contour cultivation with conservation furrows • Ridging • Sowing across slopes • Mulching • Scoops • Tied ridges • Off-season tillage • Inter row water harvesting system • Small basins • Contour bunds • Field bunds • Khadin	• Contour cultivation with conservation furrows • Ridging • Sowing across slopes • Scoops • Tide ridges • Mulching • Zingg terrace • Off-season tillage • BBF • Inter row water harvesting system • Small basins • Modified contour bunds • Field bunds • Khadin	• BBF (Vertisols) • Conservation furrows • Sowing across slopes • Tillage • Lock and spill drains • Small basins • Field bunds • Vegetative bunds • Graded bunds • Nadi • Zingg terrace	• BBF (Vertisols) • Field bunds • Vegetative bunds • Graded bunds • Chos • Level terraces

Integrated Nutrient Management

Considerable research on Integrated Plant Nutrient Supply (IPNS) has been done in India. Long-term fertilizer experiments both under irrigated as well as rainfed conditions have shown that addition of organic manures in addition to NPK results in high yields over a long period of time as compared to decline in yield over time when only inorganic fertilizers are applied, besides improving soil organic carbon content. Though benefits of organic manure application at least to replace some of the nutrient requirements of crops were well established, its usage is declining over the years. Application and management of chemical fertilizers to crops is much easier and less labor intensive while organic manure preparation, storage, transport, application etc, are cumbersome. A number of organic resources are available in India such as FYM, crop residue, live stock dung, green leaf manures, compost and vermicompost, farm waste, municipal waste etc, accounting up to 1400 million tones annually.

IPNS is also relevant for rainfed agriculture. The practice of effective use of inorganic and organic sources of nutrients in a proper proportion not only reduces the requirement of inorganic fertilizers but also improves physical conditions of soil and enhances soil water retention. Grain yields of finger millet with optimum NPK application were similar to those obtained from 50 % NPK and 10 t/ha FYM in an Alfisol at Bangalore. A three years study on an Alfisol at Hyderabad revealed that conjunctive use of organic sources of N such as loppings+ twigs of N fixing trees like *Gliricidia maculata* or *Leucaena leucocephala* + urea in 1:1 ratio (equivalent to 40 and 80 kg N/ha) gave 1.72 and 16.9 t ha^{-1} grain yield of sorghum, respectively which were at par with that obtained with 100% N applied through urea alone. The apparent recovery of N applied was more at 41,5% with conjunctive application. There are several other reports of better performance of fertilizers when used in combination with organic sources. The predominant INM recommendations for rainfed crops are listed in Table 4. The advantages of IPNS approach in arid region is also well documented. This practice also helped in improving N use efficiency of urea and fertility status of soil. Other studies on nutrient management in arid regions (rainfed) clearly indicate a positive effect of organic manures, legume based crop rotation and crop residue incorporation in maintaining soil fertility for a sustainable crop production.

Site specific nutrient management

Integrated Nutrient Management and Site-Specific Nutrient Management (SSNM) are other approaches with potential to mitigate effects of climate change (Srinivasarao *et al*., 2006, 2008, 2010a). Demonstrated benefits of these technologies are: increased rice yields and thereby increased CO_2 net assimilation and 30-40% increase in nitrogen use efficiency. This offers important prospect for decreasing GHG emissions linked with N fertilizer use in rice systems. It is critical to note here that higher CO_2 concentrations in the future will result in temperature stress for many rice production systems, but will also offer a chance to obtain higher yield levels in environments where temperatures are not reaching critical levels. This effect can only be tapped under integrated and site directed nutrient supply, particularly

Table 4 Effective Integrated Nutrient Management (INM) practices for rainfed crops across the country

Location		Fertilizer (kg ha^{-1})			
		N	P_2O_5	K_2O	
Jhansi	Cluster bean	15	60	0	Inoculation with *Rhizobium*
	Sorghum + Dolichos	60	20	0	
Rajkot	Sorghum	90	30	0	FYM@ 6 t ha^{-1}
	Pearlmillet	80	40	0	FYM @ 6 t ha^{-1}
	Groundnut	12	25	0	FYM @ 6 t ha^{-1}
	Cotton	40	0	0	FYM @ 6 t ha^{-1}
Solapur	Sorghum	50	0	0	9-10 t/ha subabul loppings can substitute 25 kg N /ha^{-1}
Indore	General	(N plus P)			4-6 t ha^{-1} FYM in alternate years
	Soybean	20	13	0	FYM @ 6 t ha^{-1}
Bijapur		(NP or NPK)			Mulching with tree lopping @ 5 t ha^{-1}
Arjia	Corn – pigeonpea	50	30	0	50 % N through organics.
	Safflower and rapeseed-mustard	30	15	0	Reduction in N by half if these crops follow legumes such as greengram/ chickpea
Agra	Barley	60	30	0	Use of FYM plus *Azotobacter*
Ranchi	Soybean	20	80	40	Inoculation with *Rhizobium*
	Groundnut	25	50	20	Inoculation with *Rhizobium*
	Pulses	20	40	0	Inoculation with *Rhizobium*
Dantiwada	Greengram	0	20	0	Inoculation with *Rhizobium*
Jodhpur	Pearlmillet	10	0	0	Addition of 10 t/ha FYM
Hoshiarpur	Corn	80	40	20	Addition of FYM
	Wheat	80	40	0	
	Chickpea	15	40	0	
Akola	Cotton + greengram	25	25	0	Along with FYM to meet 25 kg N ha^{-1}

Source: Srinivasarao *et al.* (2003)

nitrogen (N). Phosphorus (P) deficiency, for example, not only decreases yields, but also triggers high root exudation and increases CH_4 emissions. Judicious fertilizer application, a principal component of SSNM approach, thus has twofold benefits, i.e. reducing greenhouse gas emissions; at the same time improving yields under high CO_2 levels. The application of a urease inhibitor, hydroquinone (HQ), and dicyandiamide (DCD) together with urea also is an effective technology for reducing N_2O and CH_4 from paddy fields. Very little information is available on the potential of SSNM in reducing GHG emissions in rainfed crops (Srinivasarao *et al*., 2010a).

Conservation agriculture (CA)

In irrigated areas, zero tillage (ZT) has effectively reduced the demand for water in rice-wheat cropping system of Indo-Gangetic plains and is now considered as a viable option to combat climate change. ZT has some mitigation effect in terms of enhancing soil carbon, reducing energy requirement and improving water and nutrient use efficiency but actual potential has to be quantified from long term experiments. While reduced tillage is possible in few production systems in high rainfall regions in eastern and northern India, non-availability of crop residue for surface application is a major constraint, particularly in peninsular and western India where it is used mainly as fodder.

Biomass based biogas production

Large amount of energy is used in cultivation and processing of crops like sugarcane, food grains, vegetables and fruits, which can be recovered by utilizing residues for energy production. This can be a major strategy of climate change mitigation by avoiding burning of fossil fuels and recycling crop residues. The integration of biomass-fuelled gasifiers and coal-fired energy generation would be advantageous in terms of improved flexibility in response to fluctuations in biomass availability with lower investment costs. Waste-to-energy plants offer twin benefits of environmentally sound waste management and disposal, as well as the generation of clean energy (Srinivasarao *et al*., 2010a).

Livestock production has been an integral part of agriculture in India. Livestock provides an excellent recycling arrangement for most of crop residue. Most by products of cereals, pulses and oilseeds are useful as feed and fodder for livestock while that of other crops like cotton, maize, pigeonpea, castor, sunflower and sugarcane are used as low calorie fuel or burnt to ashes or left in open to decompose over time. Ideally such residue should be incorporated into soil to enhance physical properties of the soil and its water holding capacity. Lack of availability of proper chipping and soil incorporation equipment is one of the major reasons for the colossal wastage of agricultural biomass in India. Increased cost of labour and transport is another reason for lack of interest in utilizing the biomass. This is one area where little or no effort has gone in despite availability of opportunities for reasons such as aggregation, transport and investment in residue processing facilities. Many technologies like briquetting, anaerobic digestion vermin-composting and bio-char etc. exist, but they have not been commercially exploited. This area is gradually receiving attention now as a means to producing clean energy by substituting forest biomass for domestic needs. Modest investments in decentralized facilities for anaerobic digestion of agricultural residue through vermin-composting and biogas generation can meet the needs of energy deficit rural areas and simultaneously contribute to climate change mitigation.

There is renewed interest in the use of anaerobic digestion processes for efficient management and conversion of cattle dung and other agro industrial wastes (livestock, paper and pulp, brewery and distillery) into clean renewable energy and organic fertilizer source. The biogas captured could not only mitigate the potential local and global pollution but could either be combusted for electricity generation using combined heat and power generator in large to medium enterprises or used for cooking and lighting for small households. A 2 m^3 digester can generate up to 4.93 t CO_2 equivalent year^{-1} of certified emission reduction (CER). Animal wastes are generally used as feedstock in biogas plants. But, the availability of these substrates is one of the major problems hindering the successful operation of biogas digesters. It was reported that the availability of cattle waste could support only 12–30 million family-size biogas plants against the requirement of 100 million plants. A significant portion of 70–88 million biogas plants can be run with fresh/dry biomass residues. Of the available 1,150 billion tons of biomass, a fifth would be sufficient to meet this demand.

Biochar

When biomass is exposed to moderate temperatures, between about 400 and 500°C (a kind of low-temperature pyrolysis), under complete or partial exclusion of oxygen, biomass undergoes exothermic processes and releases a multitude of gases in addition to heat along with biochar. Pyrolysis produces biochar, a carbon rich, fine grained, porous substance and solid byproduct, similar in its appearance to charcoal, which when returned to soil, produces a range of environmental benefits, such as enhanced soil carbon sequestration and soil fertility improvement. Both heat and gases can be captured to produce energy carriers such as electricity, hydrogen or bio-oil which can be used as a fuel for various purposes in the process of manufacturing biochar. In addition to energy, certain valuable co-products, including wood preservative, food flavoring, adhesives etc. can be obtained (Venkatesh *et al*., 2011).

This is a novel approach to sequester carbon in terrestrial ecosystems which has several associated products in the process of its manufacture and also the end product. In India, it has been projected that about 309 m t of biochar could be produced annually, the application of which might offset about 50 % of carbon emission (292 TgC year^{-1}) from fossil fuel (Lal *et al*., 2003). Rice-wheat cropping system in the Indo-Gangetic plains of India produces substantial quantities of crop residues, and if these residues can be pyrolysed, 50 % of the carbon in biomass is returned to the soil as biochar, increasing soil fertility and crop yields, while sequestering carbon. Addition of biochar to soil has also been associated with enhanced nutrient use efficiency, water holding capacity and microbial activity. At CRIDA, research on biochar use in rainfed crops has been initiated. Biochar from castor, cotton and maize stalks was produced by using a portable kiln and used as an amendment for pigeonpea during *kharif* 2010. The crop growth was significantly superior in biochar applied plots from all three sources (Venkatesh 2010).

Agroforestry

Agroforestry systems like agri-silvi-culture, silvipasture and agri-horticulture offer both adaptation and mitigation opportunities. Agroforestry systems buffer farmers against climate variability, and reduce atmospheric loads of greenhouse gases. Agroforestry can both sequester carbon and produce a range of economic, environmental, and socioeconomic benefits; the extent of sequestration can be upto 10 t ha^{-1} in short rotation eucalyptus, leucaena plantations. Agrisilviculture systems with moderate tree density with intercrops have however lower potential.

Critical carbon input requirement for organic carbon maintenance

A long-term field experiment conducted on an Aridisol in western India was used to examine the effects of chemical fertilizers and manuring on total organic carbon (TOC), microbial biomass carbon (MBC), and particulate organic carbon (POC) in relation to crop productivity and C sequestration. The 18 years study involved perlmillet (*Pennisetum glaucum*) clusterbean (*Cyamopsis tetragonaloba*) castor (*Ricinus communis*) sequence with different soil fertility management. The latter comprised of no fertilization, 100% recommended dose of N (RDN) through chemical fertilizers, 50% RDN, 50% RDN through farm yard manure (FYM), 50% RDN through chemical fertilizers + 50% RDN through FYM, and farmer's method (5 t ha^{-1} of FYM once in 3 years). The data showed that even the addition of 33.5 t ha^{-1} C inputs through crop residues as well as FYM could not compensate the SOC depletion by oxidation, and resulted in the net loss of 4.4 t C ha^{-1} during the 18 year period. Conjunctive use of chemical fertilizers along with FYM produced higher grain yields, reduced the rate of SOC depletion than in treatments without these amendments. For every tonne increase in profile SOC stock there was an overall increase of 0.46 tonne of crop yield, and also in individual grain yield of pearl millet (0.17 t ha^{-1} yr^{-1} t^{-1} of SOC), cluster bean (0.14 t ha^{-1} yr^{-1} t^{-1} of SOC) and castor (0.15 t ha^{-1} yr^{-1} t^{-1} of SOC). The magnitude of SOC build up (R^2=0.93; P<0.05) and SOC sequestration rate (R^2=0.93, P<0.05) were proportional to the C inputs (Table 5 Figure 5). Microbial biomass carbon (MBC) and particulate organic carbon (POC) were significantly correlated (P<0.05) with SOC, which increased with application of organic amendments. Microbial quotient (MQ) and POC/ SOC ratio were

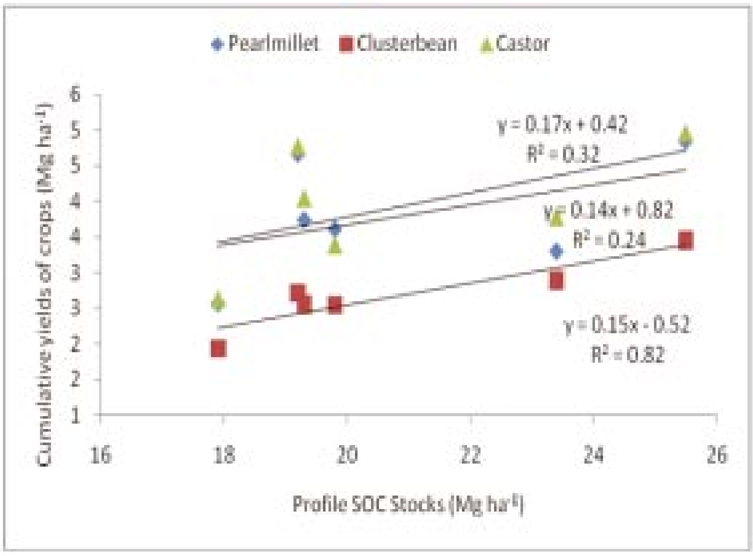

Fig 5 Influence of SOC stocks to 1-m depth on yields of individual crops in 18 year long term pearlmillet-clusterbean-castor sequence in arid condition (Srinivasarao *et al.,* 2011b; 2012c)

significantly correlated ($P<0.05$) with sustainable yield index (SYI). Threshold C input of 3.3 t C ha^{-1} $year^{-1}$ was needed to maintain SOC at equilibrium (Srinivasarao *et al*., 2011b; Mandal *et al*., 2008).

Table 5 Relationships between different forms of carbon, carbon inputs, soil carbon sequestration rate and sustainable yield index (SYI) of pearlmillet based systems in arid tropical conditions

Independent variable	Regression equation	Coefficient of determination (R^2)
Carbon sequestration rate	Y(Pearlmillet)=0.02X+0.34	0.67
	Y(clusterbean)=0.05X+0.84	0.77
	Y(castor)=0.01X+0.5	0.56
Total carbon inputs	Y(Pearlmillet) =0.003X+0.17	0.45
	Y(clusterbean)=0.008X-0.29	0.56
	Y(castor)=0.002X+0.36	0.45
Profile mean SOC content SYI	Y(Pearlmillet) =2.01X-0.07	0.61
	Y(clusterbean)=5.99X-0.44	0.77
	Y(castor)=1.64X+0.16	0.64
Microbial biomass carbon	Y(Pearlmillet) =0.004X+0.004	0.74
	Y(clusterbean)=0.01X-0.22	0.95
	Y(castor)=0.003X+0.21	0.86
Particulate organic carbon	Y(Pearlmillet) =0.0002X-0.009	0.10
	Y(clusterbean)=1.81X-0.05	0.79
	Y(castor)=0.55X+0.013	0.79

Policy issues

Apart from the use of technological advances to combat climate change, there has to be sound and supportive policy framework. The frame work should address the issues of redesigning social sector with focus on vulnerable areas/ populations, introduction of new credit instruments with deferred repayment liabilities during extreme weather events, weather insurance as a major vehicle to risk transfer. Governmental initiatives should be undertaken to identify and prioritize adaptation options in key sectors (storm warning systems, water storage and diversion, health planning and infrastructure needs). Focus on integrating national development policies into a sustainable development framework that complements adaptation should accompany technological adaptation methods (Venkateswarlu *et al*., 2011).

In addition, the role of local institutions in strengthening capacities e.g., SHGs, banks and agricultural credit societies should be promoted. Role of community institutions and private sector in relation to agriculture should be a matter of policy concern. There should be political will to implement economic diversification in terms of risk spreading, diverse livelihood strategies, migrations and financial mechanisms. Policy initiatives in relation to access to banking, micro-credit/insurance services before, during and after a disaster event, access to communication and information services is imperative in the envisaged climate change scenario. Some of the key policy initiatives that are to be considered are: mainstreaming adaptations by considering impacts in all major development initiatives facilitate greater adoption of scientific and economic pricing policies, especially for water, land, energy and other natural resources. There is urgent need for a national soil policy. Financial incentives and package for improved land management and exploring CDM benefits for mitigation strategies could be better approach. A "Green Research Fund" may be established for strengthening research on adoption, mitigation and impact assessment.

Future line of work

1) Carbon stock monitoring in Indian soils should be taken in 5 years interval. The locations, where organic carbon content has decreased, special attention should be taken in order to protect soil health and crop productivity.
2) Efforts are needed to create large scale awareness against burning of crop residues both in irrigated and rainfed agriculture.
3) Conservation Agriculture practices and their promotion need higher priority.
4) Critical carbon input requirements for major agro-ecological regions need to be computed and efforts should be taken to promote organic matter addition where ever possible.
5) On-farm generation of organic matter in terms of gliricidia should be promoted.

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Greenhouse Gas Emission from Agriculture

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Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHG) contributing 60, 15 and 5%, respectively, towards the enhanced global warming (IPCC, 2007). Methane is 25 times and nitrous oxide is 298 times more effective than CO_2 as a heat-trapping gas. Wetlands, organic decay, termites, natural gas and oil extraction, biomass burning, rice cultivation, cattle and refuse landfills are the main sources of methane whereas, removal in the stratosphere and soil are the main sinks. Primary sources of methane from agriculture include animal digestive processes, rice cultivation, and manure storage and handling. Forests, grasslands, oceans, soils, nitrogenous fertilizers, burning of biomass and fossil fuels are the sources of nitrous oxide while it is removed by oxidation in the stratosphere. Soil contributes about 65% of the total nitrous oxide emission. The major sources are soil cultivation, fertilizer and manure application, and burning organic material and fossil fuels. The main sources of carbon dioxide are decay of organic matter, forest fire, volcanoes, burning of fossil fuel, deforestation and land-use change whereas plants, oceans and atmospheric reactions are the major sinks. Though agricultural soil is a small contributor, factors such as soil texture, temperature, moisture, pH, available C and N contents influence CO_2 emission from soil.

Table 1 Atmospheric concentration, lifetime and global warming potential (GWP) of major greenhouse gases

Greenhouse gas	Atmospheric concentration	Lifetime (years)	GWP (100 years)
Carbon dioxide	387 ppm	Variable	1
Methane	1780 ppb	12	25
Nitrous oxide	319 ppb	114	298
CFC 11	250 ppt	45	4600
CFC 12	533 ppt	100	10600
HCFC 22	132 ppt	11.9	1700
HFC 23	12 ppt	260	12000

Source: IPCC (2007)

Measurement of methane and nitrous oxide emission

Methods used for measurement of GHGs vary with respect to gases that can be measured, spatial coverage, temporal resolution, cost, precision and accuracy of the method. The measured values, however, can only be properly interpreted if the various soil, plant and climatic factors, which determine the production, consumption and emission of the greenhouse gases, are taken into account. Among these, soil texture, pH, organic matter content, moisture content, nitrate and ammonium content, redox potential, plant cover, and climatic factors such as air temperature, incoming radiation, relative humidity and precipitation are important. Soil physical factors such as bulk density, porosity and pore size distribution are also important in determining the storage and movement of gases in the soil.

Two methods are generally used to measure methane and nitrous oxide emissions from soils.

- *Micrometeorology:* This method measures vertical concentration gradients of the gas using eddies correlation. It is useful for evaluating regional model simulations (scaling from site to region). However, requirement of expensive equipments and cumbersome sampling and measurement procedures restrict its use for CH_4 and N_2O measurements.
- *Soil chambers:* In this method, gas emissions from soil are determined by measuring the short-term buildup of the gas in a sealed enclosure placed over the soil surface. This restricts the volume of air exchange across the covered surface. Any net emission or uptake from soil can be measured as a change in concentration of the gas.

This chapter deals with the soil closed-chamber method only as it is a most widely used and relatively inexpensive method to estimate GHG emissions from soil.

Closed-chamber method

Gas flux from the soil using closed-chambers can be determined by collecting gas samples periodically from the chambers and measuring the change in concentration of a gas with time during the period of linear concentration change (Hutchison and Mosier, 1981). Chambers can be made from material like rigid plastic, metal or acrylic sheets. For collecting gas samples from crop fields, generally, chambers of 50 cm × 30 cm × 100 cm (Fig 1) made of 6 mm acrylic sheets are used. Aluminum channels, used with each chamber, are inserted 10 cm inside the soil and the channels filled with water to make the system air-tight. A battery operated fan is fixed inside the chamber to homogenize the inside air. A thermometer is inserted to monitor the inside temperature. One 3-way stopcock/or a silicon septa is fitted at the top of chamber to collect gas samples. Gas samples are drawn with the help of hypodermic needle (24 gauge) at 0, 1/2 and 1 hour after placing the chamber on the alluminum channel. After drawing the sample, syringes are made air-tight with a three-way stopcock. Samples of four replications of each treatment are taken from the plots and the average is

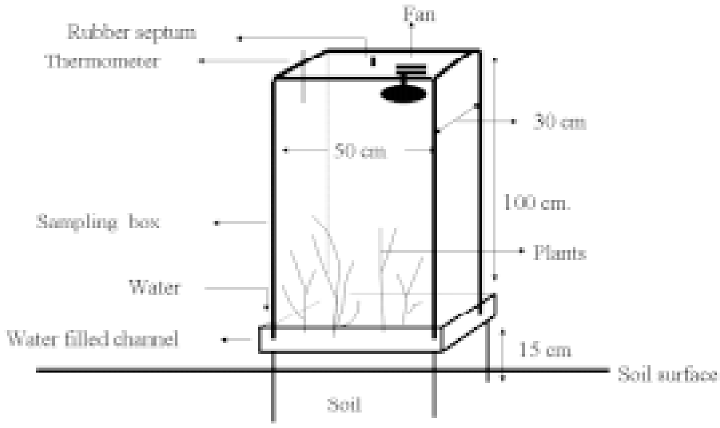

Fig 1 Closed-chamber used for collection of methane and nitrous oxide samples from field

taken as representative value for the treatment. Head space volume and temperature inside the chamber is recorded, which is used to calculate flux of gas.

To make a flux measurement, the chamber is fixed on the top of the pre-inserted aluminum channels. The change in CH_4 or N_2O concentration in the chamber so formed, with time is determined by taking replicate gas samples from the chamber headspace with a syringe. About 20-50 mL capacity plastic or preferably greased glass medical syringes fitted with a 2-way or 3-way loop, are generally used. Gas samples should be taken from the headspace immediately after sealing and at equal time intervals thereafter over a period not exceeding 2 hours. A minimum of three measurements should be made to check the linearity of concentration increase in the chamber. A departure from a straight line indicates either an inadequately sealed chamber or the decrease in gas concentration gradient between the zone of production in the soil and the chamber atmosphere changes the gas diffusion rate with time. The gas samples immediately transferred to the vacuutainers and analyzed in the gas chromatograph (GC). The chamber cover should be removed after the final sample to minimize the disturbance to environmental conditions within the enclosure formed by the chamber wall.

To transfer gas samples over long distances to the analytical laboratory, evacuated vials fitted with rubber/silicon septa (e.g., vacutainers/exetainers) can be used satisfactorily. The septa on the vials should be cleaned with a detergent and the vials evacuated by a vacuum pump before use. An alternative method is the use of glass serum bottles fitted with butyl rubber stoppers. The vials are taken to the sampling site, and filled with the gas sample with a syringe. By injecting sufficient sample to achieve an over-pressure, e.g., 10 mL into a 9 mL vial, contamination problems are prevented.

The methodology has been illustrated step-wise as follows.

1. Collection of gas samples

- Gas sample is collected using closed-chamber technique (Fig 1).
- Chambers of 50 cm × 30 cm × 100 cm size (according to experiment) made of 6 mm acrylic sheets are required for sampling.
- An aluminum channel is placed in the field and is used with each acrylic chamber.

- The aluminum channels should be inserted 10 cm inside the soil and the channels filled with water to make the system air- tight.
- One 3-way stopcock (Eastern Medikit Ltd. India) is fitted at the top of chamber to collect gas samples.
- The chamber should be thoroughly flushed several times with a 50 ml syringe to homogenize the inside air thoroughly.
- Gas samples are to be drawn with 20-50 mL syringe with the help of hypodermic needle (24 gauge).
- After drawing sample, chambers should be made air tight with three way stop cock.
- Head space volume inside the box should be recorded, which will be used to calculate flux of nitrous oxide and methane.
- Gas samples at 0, 1/2 and 1 hrs are collected from the chamber.

2. Analysis of gas samples

Methane

Concentration of methane in the gas samples is analysed by Gas Chromatograph fitted with a flame ionization detector (FID). The FID is used for detection of substances, which produce ions when heated in an H_2-air flame. The detector is insensitive to permanent gases, water and inorganic ions, which do not ionize at 2100 ^oC. The sample along with the carrier gas (eluent) enters the hydrogen jet via millipore filter. The sample components get ionized to form ions and free electrons on entering the flame at the tip of the jet. The electrons produced are drawn towards the collector. Hence there is a flow of current. The current flow across an external resistor, sensed as a voltage drop, is amplified and displayed on the recorder. The entire assembly is housed in an oven to prevent condensation of water vapour formed as a result of combustion.

Gas samples containing methane are introduced into the gas chromatograph by a syringe fitted with a two-way nylon stopcock through a sampling valve. A gas sample loop of 1 or 2 cm^3 is fitted to the sample valve. It is possible to inject manually, however, the use of a sample loop is to be preferred. The configuration of the valve is normally designed to fit the needs of the user. Methane analysis can be accomplished by various modifications of GC settings and column materials. Each individual setting will have to be optimized empirically in order to achieve a satisfactory separation and detection. Methane can be separated from other gaseous components on a Porapak N or Porapak Q maintained at 50 °C having a carrier gas flow (helium, nitrogen or argon) of 20-30 $cm^3\ min^{-1}$ An alternative is the use of a molecular sieve (13 x 60-80 mesh size) as a column material and synthetic air as carrier gas. Methane is detected using a FID maintained at 250 °C. Column temperature is 70°C. H_2 with a flow rate of 30-40 ml min^{-1} is used for FID. The sampling valve can be accentuated manually or time-controlled pneumatically or electronically using computer or GC-contained microprocessor. A GC-computer interface is used to plot and measure the peak area. The

CH_4 standards (1, 5 and 10 ppm) are used as a primary standard.

Calculation of methane flux

Cross-sectional area of the chamber (m^2)	=	A
Headspace (m)	=	H
Volume of headspace (L)	=	1000 X AH
CH_4 concentration at 0 time ($\mu L\ L^{-1}$)	=	C_o
CH_4 concentration after time t ($\mu L\ L^{-1}$)	=	C_t
Change in concentration in time t ($\mu L\ L^{-1}$)	=	$(C_t - C_o)$
Volume of CH_4 evolved in time t (μL)	=	$(C_t - C_o)$ X 1000 AH
When t is in hours, then flux ($mL\ m^{-2}\ h^{-1}$)	=	$[(C_t - C_o)$ X AH)]/(A X t)

Now 22.4 mL of CH_4 is 16 mg at STP

Hence, Flux = $[(C_t - C_o)/t]$ X H X 16/22.4 X 10000 X 24 mg $ha^{-1}\ d^{-1}$

Nitrous oxide

Concentration of nitrous oxide in the gas samples is analysed by Gas Chromatograph fitted with an electron capture detector (ECD) and 6' x 1/8" stainless steel column (Porapak N). The ECD is used for the detection of those substances which have affinity for electrons. The detector consists of two electrodes, one of which is treated with radioactive ^{63}Ni, which emits beta rays. These high-energy electrons bombard the carrier gas (N_2 or argon mixture) to produce large numbers of low energy (or thermal) secondary electrons. The other positively polarized electrode collects these electrons. This steady state current is reduced when an electrophilic sample component passing through the gap between the two electrodes captures some of these electrons thus providing an electrical reproduction of the GC peak. This detector can also contain some other radioactive elements besides ^{63}Ni like tritium or scandium. Although the sensitivity of ^{63}Ni is lower but it remains constant for a longer duration and surpasses the sensitivity of the tritium cell of the same age.

The temperatures of column and detector are kept at 50°C, and 320°C, respectively. The flow rates of carrier, back flush and detector purge gases (95% argon + 5% methane or N_2) are kept as 14-18 $cm^3\ min^{-1}$. Gas samples are introduced into a gas sampling loop (size depends upon the sensitivity of the ECD used) through an inlet system. Both CO_2 and water vapours are removed from the gas samples. The two absorbent traps are prepared by packing 10 mm millipore syringe filter holders with Ascarite and $MgClO_4$.

A GC-computer interface is used to plot and measure the peak area. The N_2O standard (500 ppbV) is used as a primary standard.

Calculation of N_2O flux

Cross-sectional area of the chamber (m^2)	=	A
Headspace (m)	=	H
Volume of headspace (L)	=	1000 X AH
N_2O concentration at 0 time ($\mu L\ L^{-1}$)	=	C_o
N_2O concentration after time t ($\mu L\ L^{-1}$)	=	C_t

Change in concentration in time t ($\mu L\ L^{-1}$) = (C_t - C_o)
Volume of N_2O evolved in time t (μL) = (C_t - C_o) X 1000 AH
When t is in hours, then flux ($mL\ m^{-2}\ h^{-1}$) = [(C_t-C_o) X AH)]/(A X t)
Now 22.4 mL of N_2O is 44 mg at STP
Hence, Flux = [(C_t - C_o)/t] X H X 44/22.4 X 10000 X 24 mg $ha^{-1}\ d^{-1}$

Advantages of the closed-chamber method

- Very small fluxes can be measured.
- No extra equipment requiring electrical supply is needed.
- There is little disturbance of the site due to the short-time for which the cover has to be placed for each gas flux estimate.
- The chambers are simple and relatively inexpensive to construct with a variety of readily available materials, which are inert for the gas of interest.
- Chambers can be installed and removed easily facilitating measurement.
- Useful for addressing research objectives served by discrete observation in space and time.
- In combination with appropriate sample allocations, it is adaptable to a wide variety of studies on local to global spatial scales.
- Particularly well suited to *in situ* and laboratory based studies addressing physical, chemical and biological controls of surface-atmosphere trace gas exchange.
- Good for short deployment period and low exchange rate.

Precautions to be taken

While using the closed-chamber technique for GHG flux measurement, following precautions should be taken.

- Chamber height should be more than 30 cm.
- The chamber headspace N_2O concentration at zero hour should be measured accurately. For this the first air sample inside the chamber should be taken immediately after the chamber placement on the channel/collar in case of cylindrical chambers.
- Air samples should be taken in as short a time as possible to observe a measureable increase in headspace gas concentration. Longer chamber deployment durations may result in negative impacts.

Limitations of the method and ways to overcome those

In spite being simple and popular, the closed-chamber method suffers from the following limitations.

- Concentrations of gas in the chamber can build up to levels where they inhibit the normal emission rate. However, the problem can be minimized by using short collection periods.

- Closed-chambers alter the atmospheric pressure fluctuations, which are found at the soil surface due to the natural turbulence of air movement. Thus, a closed-chamber may underestimate the flux of the gas. The problem may be overcome by an appropriately designed vent, which allows pressure equilibration in and outside the chamber.
- Temperature changes in the soil and inside the chamber can occur. However, insulating the chamber and covering it with a reflective material can reduce temperature differences.

For obtaining round the clock emission measurements and to overcome some of the above limitations, automatic sampling devices are very useful. In this device, the air samples from the inner volume of the gas collecting chamber are replaced by a gas flow system providing a periodic sample transfer to the gas chromatograph. Automatic sampling devices are costly and their use is confined to those locations where the laboratory is in the vicinity of the experimental field. The automatic sampling system may be extensively used in the long-term field measurements of GHGs at different experimental stations. The basic components of an automatic sampling system are: Gas collecting chambers (boxes) equipped with removable covers, gas flow system (tubing, pump), sampling unit, analytical unit (GC and integrator), time control and data acquisition systems. It allows continuous round the clock and simultaneous measurements at several locations for an entire growing season, as is necessary for obtaining data on diurnal and seasonal variations in emission rates under field conditions.

Practical considerations to reduce the uncertainties

- Number of chambers: Due to high spatial variability, more the number of chambers, the less is the uncertainty.
- Sampling frequency: Due to high temporal variability, the more often we sample the less is the uncertainty.
- Chamber size: Due to high microscale variability, bigger is usually better.
- Chamber deployment time: Longer period of sampling results in better precision; too long, however, may yield sampling artifacts.

Measurement of carbon dioxide emission from soil

For quantitative analysis of CO_2 emission from soil four methods are used: (1) alkali trap method, (2) soil respirator method, (3) infrared gas analyzer method, and (4) closed-chamber method.

(1) Alkali trap method

With this method CO_2 that is trapped in an aqueous solution of alkali (usually KOH or NaOH) is precipitated as $BaCO_3$ by the addition of excess $BaCl_2$. The precipitate is collected, washed, dried and weighed. The volumetric analysis for CO_2 trapped in aqueous alkali is a popular method because of its simplicity and high degree of sensitivity. For measurement of CO_2 evolution, alkali of a defined concentration is placed in an open jar above the soil surface, and the area to be measured is covered with a metal cylinder closed at the upper end. The CO_2 evolved from the soil surface is trapped in the cylinder and remains confined there until it is absorbed by the alkali. After a certain period of time, the alkali is removed and its unreacted portion is determined by titration. By subtraction, the amount of CO_2 that combined with the alkali is determined.

A CO_2 trap is prepared by pipetting 20 mL of 1*N* NaOH into a glass jar and placed it on a tripod stand. Immediately the metal cylinder is placed over the alkali trap, and pressed the edge by about 2 cm into the surface of the soil. The cylinder should be shielded from direct sunlight by either covering it with a sheet of wood or a piece of aluminum foil. After exposure of the alkali for 2-4 hours, the jar is removed, covered with lids (airtight seal), and brought to the laboratory for analysis. Controls for this experiment consist of jars of alkali that are incubated in the field in completely sealed metal cylinders by closing the open ends with tightly fitting lids. The airtight seal between lid and cylinder can be obtained by smearing the edge with silicon grease. The alkali solutions from the controls and those exposed to soil air are titrated to determine the quantity of alkali that has not reacted with CO_2. For this purpose, excess $BaCl_2$ is added to the NaOH solution to precipitate the carbonate as insoluble $BaCO_3$. A few drops of phenolphthalein are added as indicator, and titrated with HCl directly in the jar. The acid should be added slowly to avoid contact with and possible dissolution of the precipitated $BaCO_3$. The volume of acid needed to titrate the alkali is noted. The amount of CO_2 evolved from the soil during exposure to alkali may be calculated using the formula:

$$\textit{Milligrams of C or } CO_2 = (B - V)\, NE$$

Where, B = volume (mL) of acid needed to titrate NaOH in the jars from the control cylinders, V = volume (mL) of acid needed to titrate the NaOH in the jars exposed to the soil atmosphere, N = normality of the acid, and E = equivalent weight. To express the data in terms of carbon, E = 6; to express it as CO_2, E = 22. Once the milligrams of CO_2-C or CO_2 have been determined, the data are conveniently expressed as mg of $CO_2\ m^{-2}\ h^{-1}$.

(2) Soil respirator method

The soil respiration i.e., flux of CO_2 per unit area per unit time, is measured by placing a closed-chamber on the soil and measuring the rate of increase of the CO_2 concentration inside the chamber. The soil respiration system consists of a soil respiration chamber (SRC) and an environmental gas monitor (EGM). For soil respiration, a chamber of known volume is placed on the soil and the rate of increase in CO_2 within the chamber is monitored. With this system, the air is continuously sampled in a closed circuit through the EGM and the soil respiration rate is calculated, displayed and recorded by the analyzer. The air within the chamber is carefully mixed to ensure representative sampling without generating pressure differences, which would affect the evolution of CO_2 from the soil surface.

It is assumed that the rate of increase in CO_2 is linear, though any leakage will cause a decline in its concentration with time. A quadratic equation is fitted to the relationship between the increasing CO_2 concentration and elapsed time. The flux of CO_2 per unit area and per unit time is measured using the following equation.

$$R = \frac{(Cn - Co)}{Tn} X \frac{V}{A}$$

Where R is the soil respiration rate (flux of CO_2 per unit area per unit time), Co is the CO_2 concentration at T=0 and Cn is the concentration at a time Tn, A is the area of soil exposed and V is the total volume of the chamber.

(3) Infra-red analyzer method

Carbon dioxide can be sampled and analysed using Infra red-based continuous soil CO_2 flux analyser (LI-8100). The LI-8100 system can be used with a 20 cm short term survey chamber to obtain soil CO_2 flux. The closed-chamber is placed on the soil and the rate of increase of the CO_2 concentration in the chamber is used to determine the soil flux. CO_2 diffuses out of the soil in response to the concentration gradient between the soil pore spaces and the atmosphere. As the chamber CO_2 concentration increases, the concentration gradient between the soil and the chamber air decreases. This causes the measured soil CO_2 flux to decrease exponentially with time. The desired value of the soil flux can be determined when the chamber CO_2 concentration is the same as the ambient atmospheric concentration. The flux can be estimated using the initial slope of a fitted exponential curve at the ambient CO_2 concentration. This is done to minimize the impact of the altered CO_2 concentration gradient across the soil surface after chamber was closed.

(4) Closed-chamber method

The CO_2 flux from the soil using closed-chambers can be determined by collecting gas samples periodically from the chambers and measuring the change in concentration of a gas with time during the period of linear concentration change similar to sampling of methane and nitrous oxide. The analysis can be done in gas chromatograph fitted with FID and a methanizer. The methanizer consists of a 6" x 1/8" stainless steel tube which is mounted alongside the edge of the heated valve oven, and thermostated to 380ºC. The tube is packed with a special nickel/zinc/Pt-Pd catalyst powder. Column effluent is mixed with 20 $mLmin^{-1}$ of hydrogen prior to the methanizer entrance. Under these conditions, CO and CO_2 are converted to methane while passing through the methanizer. Hydrocarbons such as methane, ethane and propane pass through the methanizer unaffected. Because the CO and CO_2 are converted to methane, they can be detected by the FID down to 1 ppm. CO_2 is about 380 uL L^{-1} in air, but CH4 is only about 1.8 uLL^{-1}, the CO_2 response (after conversion to CH_4) on the FID is much greater than the CH_4 (in air samples). Methanizer tubes can be poisoned by large amounts of sulfur gas. Calculation of flux can be done similar to methane as CO_2 is measured as methane (discussed above).

The CO_2 concentration in samples can also be analyzed using gas chromatograph equipped with thermal conductivity detector (TCD) and 3 m long and 0.3 cm internal diameter Hayesep D column. Helium is used as a carrier gas at a flow rate of 25 cm^3 min^{-1}. Oven and detector temperatures are 50 and 150 °C, respectively. Standard CO_2 samples are to be used for GC calibration. Flux of gases (F, g CO_2-C m^{-2} day^{-1}) can be computed as:

$$F = (\square g/\square t)\ (V/A)k$$

Where $\square g/\square t$ is the linear change in CO_2 concentration inside the chamber (g CO_2-C m^{-3} min^{-1}); V is the chamber volume (m^3); A is the surface area of the chamber (m^2) and k is the time conversion factor (1440 min day^{-1}). Chamber gas concentration can be converted from molar mixing ratio (ppm) determined by GC analysis to mass per volume by assuming ideal gas relations. Hourly CO_2 fluxes are calculated from the time vs. concentration data using linear regression.

Global warming potential

Global warming potential (GWP) is the index that has been developed to compare different GHGs on a common reporting basis. CO_2 is used as the reference gas to compare the ability of a particular gas to trap atmospheric heat relative to CO_2. Thus, GHG emissions are commonly reported as CO_2 equivalents (e.g. tons of CO_2 eq.). The GWP is a time integrated factor, thus the GWP for a particular gas depends upon the time period selected. A 100-year GWP is the standard that has been broadly adopted for GHG reporting (Table 1). The GWP of agricultural soils may be calculated using the following equation (IPCC 2007).

$$GWP = CO_2 + CH_4 * 25 + N_2O * 298$$

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Soil Organic Carbon Mapping of Northeastern Region of India: *a Geographic Information System Approach*

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Introduction

Soil organic carbon (SOC) is considered to be one of the most important indicators of productivity of the low input farming systems and assessment of the soil health. It is the key to soil fertility, productivity and quality, as decline in SOC is considered to create an array of negative effects on land productivity. Hence, maintaining and improving its level is pre-requisite to ensuring soil quality, future productivity, and sustainability (Katyal *et al*., 2001). The SOC not only affects sustainability of agricultural ecosystems, but also extremely important in maintaining overall quality of environment as soil contains a significant part of global carbon stock: 3.5% compared to 1.7% in atmosphere, 8.9% in fossil fuels, 1% in biota and 84.9% in oceans. There is a growing interest in assessing the role of soil as a sink for carbon under different agricultural management practices and other land uses including forest ecosystems (Leite *et al*., 2003), because some estimates claim that increase in soil organic carbon (SOC) content by 0.01% would lead to the C-sequestration equal to the annual increase of atmospheric carbon dioxide concentration (Lal *et al*., 1998). Thus, organic carbon management is the key to environment management and sustainability of soil health *vis-a-vis* agricultural productivity. Reasonable amount of information on soil organic carbon status and carbon stock for different agro-ecological zones in spatial scale and their interaction with climate change implications based on past and present scenarios, projections of possible changes in future climate scenario etc. has been generated for main land India (Ajtay *et al*., 1979; Dadhwal and Nayak, 1993; Chhabra *et al.,* 2003 Bhattacharyya *et al*., 2009 and Singh *et al*., 2011).

Northeastern region of India, by virtue of its strategic setting in the high rainfall eastern Himalaya, one of the mega-biodiversity hotspots in the world has unique place in India because of its rich ness in phytobiomass (above & below ground) in the form of forest and allied sources. Biomass is one of the most important sources to enrich the soil with organic carbon or organic matter. Landuse land cover change and type of landuse practices have considerable influences on soil carbon inventories, global C cycles, sink-source balance, aggredation- degradation pace of soil health in cultivated area, carbon sequestration and emission pathways. Conversion of native/primary forests to agricultural land, grasslands/ pastures, regeneration of secondary vegetation with forest clearing and other vegetations has varying influence on soil carbon contents and stocks (increase/decrease); depending on the type of forest ecosystems undergoing change and post land conversion managements (Post and Kwon, 2000).

Landuse pattern in NE region of India depicts a distinct pattern as compared to rest of the country. Abrupt land transformation and land cover change due to large scale deforestation by over exploitation of forests for fuel, timber and fodder surrounding human settlement, clearing of forest lands to temporary agricultural land through adoption of jhuming on hill slopes, shortening of jhum cycle with cultivation of erosion permitting crops along the steep slopes (>60%), conversion of natural forests into horticultural plantations, lack of land ownership rights, burgeoning increase in population including livestock, infra- structure development, extensive mining activities, soil acidification and other faulty anthropogenic interventions are some of the most common land degradation forces presently operating in NE region. Extensive information at spatial scale to assess the status of soil organic carbon and the estimation of carbon stocks at regional level is limited. Similarly, spatial information at regional scale on landuse-land cover pattern/change of the fragile hilly ecosystems of NE region is also lacking. Erratic rainfall distribution pattern (frequency, intensity and amount) at spatial and temporal scales across NE region is another bottleneck, since rainfed agriculture dominates the food grain production of NE Region; therefore, any abrupt change in climate variables, more particularly rainfall patterns, poses serious threat to soil carbon status, soil health and consequently food and environmental security of the region. However, with the advent of geospatial tools like satellite remote sensing and its integration with geographic information system (GIS) and traditional point based observation, it is now possible to create land use – land cover map from multi-temporal data and generate spatial databases on natural resources including soil carbon inventories at regional scale. Realizing the needs**,** we have prepared spatial map of SOC content, and carbon density-stocks in GIS environment using large geo-coded data base compiled from published literatures and our own intensive field based observations across NE region. The outcome of this finding would give a new dimension to landuse planning, agricultural area diversification, and future projection studies at regional level. It would also help in devising location specific mitigation and adaptation strategies related to carbon sequestration and climate resilient agriculture.

Materials and Methods

Study area

The study area selected for the present study comprises six Northeastern states of India *viz*., Assam, Meghalaya, Manipur, Nagaland, Tripura and Sikkim and has a total geographical area of 15.61 Mha which is nearly 4.8% geographical area of the country

Map 1 Study area representing NE Region of India

(India) with more than forty-three million populations. About 35% area in the region is plain excepting Assam where plains account for 84.44% of its total geographical area. Net sown area is highest in Assam (34.12%) followed by Tripura (23.48%). Cropping intensity is highest in Tripura (156.5%) followed by Manipur (152.1%), and Assam (123.59%).

Climate and soil type of NE region

The region experiences hot summer and cold winter. The temperature varies from as low as 0°C in Himalayan range to 35°C in some parts of Tripura. The region falls under high rainfall areas, with Cherapunji Plateau receiving over 11000 mm during monsoon season. The region is characterized by steep to very steep slopes in Meghalaya, Manipur, Nagaland, and Sikkim and gentle slopes in Assam valley. The vegetation comprises sub-tropical broad leaf, coniferous (pine including woody and herbaceous species) and bamboo types. The topography, climate and vegetation have, therefore, played a great role in the formation of a variety of soils in the region. These could broadly be put under Red and Yellow, Brown Hill, Old and Recent Alluvial and Terai soils. Soil is mostly acidic in reaction and acid soils (pH<6.5) occupy nearly 81% of total geographical area (TGA= 26.29 mha) of NE region. Acidic soils below pH 5.5 occupy around 16.2 mha (61.5% of TGA) of NER (Sharme *et al.,* 2006). Soil acidity induces imbalance in availability-deficiency-toxicity of nutrient elements required for optimum plant growth. Presence of the toxic concentration of Al^{3+} and to a lesser extent Mn^{2+}, deficiency of bases (Ca, Mg, K) due to extensive leaching and their poor retention power in clay complex, high P-fixation in of soils caused by highly active Al^{3+} and Fe^{3+} surfaces are some of the major constraints in achieving average crop productivity of more than 1 t ha^{-1} in the region (Sharme *et al.,* 2006).

Data sources

Data on soil texture (sand, silt and clay content) and soil organic carbon status of surface layer under different landuse systems were collected from 285 locations of the region from different sources like soil survey, published reports, peer reviewed research articles and reports published by research institutes located in the region. In addition to 285 geo-coded observations, we also collected 457 geo-referenced composite surface soil samples (0-15 cm), representing various landuse practices from different reaches of the hillock (upper, middle and lower reaches) across six states of NER. So, all together, seven hundred forty two (742) numbers of observations (sample size) representing major landuses namely forests (dense, open/secondary /scrub), agriculture (crop land), shifting cultivation, plantation crops, grass and wastelands lands were considered in the present study for spatial mapping of soil organic carbon content across NER (except Mizoram and Arunachal Pradesh).

The collected 457 soil samples were air dried, crushed and grounded to pass through a 0.5 mm sieve and then analysed for soil organic carbon (SOC) estimation. The SOC was determined by the wet digestion method of Walkley and Black (Nelson and Sommers, 1982). Soil textural class was determined from 2 mm grinded samples by Hydrometer method (Bouyoucos, 1962).

Computation of soil bulk density and organic carbon stocks

1. Soil bulk density was estimated using pedo-transfer function (PTF's) developed by Ravinder Kaur *et al*., (2002).
2. Due to the non-availability of PTF models representing the Soil properties under major condense system of the region, in the present study, we used PTF's developed by Ravinder Kaur *et al*., (2002) for estimation of bulk density values.
3. A perusal of literature revealed that among the available PTF models, the model developed by Ravinder Kaur *et al*., (2002 suits well for our study area. Since the model has been developed and validated on hilly ecosystems of Western Himalayan Region of India which is comparable to our study area, and also the model was based on both soil OC and soil texture data base. The algorithms is as follows

Bulk density (gm cm^{-3}) =

$$\text{Exp}\ \{0.313 - 0.191\ (\%OC) + 0.021(\%clay) - 0.00048\ (\%\ clay)^2 - 0.00432\ (\%silt)\} \ldots(i)$$

SOC densities were estimated from the SOC contents, estimated BD values and the corresponding soil depth following the equation (Post and Kwon, 2000):

$$\text{SOC density in soils (t } ha^{-1}) = \text{SOC (g } g^{-1}) \text{ x BD (g } cm^{-3}) \text{ x soil depth (cm)}\ldots\ldots(ii)$$

GIS mapping of spatial distribution of SOC content and SOC density in NER

To study the spatial distribution of soil organic carbon across NER (excluding Arunachal Pradesh and Mizoram), a point layer was generated in GIS environment (Arc GIS 9.3 software) by entering latitude-longitude values of sampling sites. There were 742 points in the layer and each point in the layer represents a location where the SOC had been measured. The percent SOC was entered in the attribute table. By interpolation of this point layer in Arc GIS 9.3 using kriging, soil organic carbon map was generated. Kriging is an advanced geo-statistical procedure that generates an estimated surface (i.e., map) from a scattered set of points with z-values (i.e., attribute values). The soil organic carbon map was classified into five classes representing SOC content (%) namely - 0.50- 1.0, 1.0-1.5, 1.5-2.5, 2.5-3.5 and 3.5-5.5%. To get state wise area statistics, state boundaries of respective states were overlaid on SOC map and finally, area under different classes of SOC contents (%) in each state was estimated under these five categories. Similarly, spatial map on SOC density (t ha^{-1}) was prepared with 6 categories namely 16-20, 20-25, 25-30, 30-35, 35-40 40-50 and 60-80 t ha^{-1}, respectively and the corresponding area in each states under the six classes has been presented.

Results and discussion

Descriptive statistics on agrophysical and soil properties across NE Region

Descriptive statistics of agro-physical and soil properties have been presented in Tables 1 & 2. Six states of NE region (excluding Arunachal Pradesh and Mizoram) were selected and from each state, varying number of observations on soil texture (sand, silt and clay %) and SOC content were collected. Relatively large sample size was selected for Assam since the geographical area of the state is 3-5 times higher compared to other five NE states. The observations on rainfall, soil texture and SOC represented a wide range of altitudinal variation: from 20 m from mean sea level (Assam) to as high as 3500 m (Sikkim). Among the six states, average elevation from mean sea level (msl) representing sampling site was highest in Sikkim (1835 m), followed by Nagaland (1143 m), Manipur (888 m) and Meghalaya (503 m). Sampling sites from Assam and Tripura were located considerably at low altitude (86-108 m from msl) (Table 1). Average annual rainfall distribution also reflected a considerable spatial variation among and within each states of NE region.

Meghalaya registered highest mean annual rainfall as well spatial variation (3067±3000 mm) followed by Sikkim (2941±755 mm) and Assam (2368±573 mm). Among the six NE states, Nagaland receives lowest mean annual rainfall (1540 ±443 mm), just next to Manipur (1816±349 mm) (Table 1).

Sampling depth for SOC content varied widely within each state across all landuse practices. Average sampling depth was highest in Sikkim (18.6 cm) followed by Nagaland

Table 1 Descriptive statistics on agro-physical parameters across the study area

State	Elevation, m	Annual rainfall, mm
Assam	20-1220 (86#)	1318-3225 (2368)
Manipur	150-1800 (888)	1353-2088(1816)
Meghalaya	18-1625 (503)	1280-11455 (3067)
Nagaland	160-2406(1143)	1120-2619(1540)
Sikkim	700-3500(1835)	1300-3900 (2941)
Tripura	30-710(108)	2000-3203 (2367)

* Standard deviation # Mean of three years

(17.6 cm) and Manipur (16.6 cm) while Tripura had lowest sampling depth (14.6 cm). This variation in sampling depth was mostly due to varied surface horizon thickness of the routine soil survey data base compiled from secondary sources Table 2). Soil textural class also reflected wide variation from sandy to clay within as well as among the states. Average per cent sand content varied from 26.9 (± 16.4) in Nagaland to 47.3 (±23.1) in Meghalaya while silt content (%) varied from 28.4 (±14) in Tripura to 40.6 (±18) in Sikkim. Similarly, clay contents (%) varied from 18.8 (±7.7) in Sikkim to 32.6 (±8.8) in Nagaland (Table 2).

Table 2 Descriptive statistics on soil properties across NE Region of India

State	Sampling depth, cm	Textural class	Sand (%)	Silt (%)	Clay (%)	Bulk density Mg m^{-3}	SOC (%)
Assam	16.0±4.2*	Sandy-clay	40.7±22.8	34.6±16.4	24.7±16.4	1.24±0.19	0.47-3.76 (1.32#±0.54*)
Manipur	16.6±3.3	Loamy sand-clay	33.2±16.7	36.5±13.1	30.3±9.7	1.03±0.20	1.06-5.74 (2.13±0.88)
Meghalaya	15.6±2.7	Loamy san-clay	47.3±23.1	28.9±16.8	21.0±11.9	1.09±0.19	0.73-9.12 (2.08±1.05)
Nagaland	17.6±3.5	Sandy loam-clay	26.9±16.4	40.5±11.8	32.6±8.8	1.01±0.22	0.86-5.96 (2.36±1.16)
Sikkim	18.6±5.5	Gr. loam-cl.loam	41.4±19.6	40.6±18.0	18.8±7.7	0.88±0.16	1.50-5.90 (2.99±1.01)
Tripura	14.6±2.3	Sandy loam-clay	44.8±19.0	28.4±14.0	26.8±7.9	1.31±0.18	0.42-3.60 (1.23±0.56)

* Standard deviation

Surface SOC content also varied large variation across study area, with four states falling under very high category (2.08-2.99%) while the remaining two states had relatively less SOC content (1.23-1.32%). Among the six NE states, average SOC content (%) was highest in Sikkim (2.99±1.01) followed by Nagaland (2.36±1.16), Manipur (2.13±0.88) and Meghalaya (2.08±1.05) while Assam (1.32±0.54) and Tripura (1.23±0.56) recorded lowest SOC content (Table 2). Among the NE states, Assam and Tripura recorded SOC content less than 0.5% in few locations.

Estimated average BD values (Mg m^{-3}) computed from soil texture (silt and clay) and SOC dependent PTF developed by Kaur *et al*.,(2002) reflected a variation from as low as 0.88 (±0.16) in Sikkim to as high as 1.31 Mg m^{-3}(±0.18) in Tripura. Estimated BD values reflected a strong negative correlation with SOC (r= - 0.786), silt (r = - 0.587) and clay (r = - 0.399) contents while sand reflected a positive correlation (r = +0.587). Since Sikkim had significantly higher SOC content and Assam and Tripura had lowest SOC contents, BD values were lower in Sikkim and higher in Assam and Tripura. Meghalaya, Manipur and Nagaland had comparable BD values (1.01 -1.09 Mg m^{-3}).

Extent and spatial distribution of landuse-land cover pattern across NE region

Landuse-land cover statistics generated from multi-temporal satellite data of LISS-III analysis (NRSC, 2011) reflected that Assam was the only states of NE region with more than 30% of total geographical area (TGA) under agriculture while Tripura and Nagaland occupied only 11.3-12.9% TGA (Table 3). Other three states namely Sikkim (9.6%), Manipur (7.5%) and Meghalaya (6.5%) are having less than 10% geographical area under agriculture. Area under dense forest cover (>40% canopy coverage) is maximum in Tripura (51.7% of TGA) while lowest is in Assam (16% of TGA). The remaining four states namely Manipur, Meghalaya, Nagaland and Sikkim are having 25.1-28.9% of TGA under dense forest. Area under open/secondary forests with canopy coverage of less than 40% and concentrated in the vicinity of settlements is marginal in Nagaland (0.3%), Meghalaya (1.5%) and Assam (4.5%). However, Manipur, Sikkim and Tripura have more than 10 % of TGA (10.3-11.5%) under open forest. Area under plantation crops like tea, coffee, rubber and other horticultural fruit trees are negligible (0.1-2.4%) except in Assam and Tripura where nearly 5.0% of TGA is under plantation crops, which might be due to the significant presence of tea plantation in Assam and rubber plantation in Tripura. Similarly, area under shifting cultivation (current) is also very negligible (< 4% of TGA) in all the 4 states except Nagaland which is having more than 9% TGA under Shifting cultivation (Table 3). Unlike other NE states, Sikkim doesn't have any area under shifting cultivation. About one third area of the state (36.7% of TGA) is snow covered. Waste/grass lands occupy significant chunk of area (11.2-14.9% of TGA) in all the states except Assam (8%) and Tripura (4.9%).

Table 3 Landuse –land cover statistics of NE India derived from multi-temporal remote sensing data of IRS-P6-LISS-III sensor (2004-2005)

N.E. States of India	Assam	Manipur	Meghalaya	Nagaland	Sikkim	Tripura	Total
Geographical area (Mha)	7.79	2.22	2.24	1.65	0.70	1.02	15.61
Land use class (% of geographical area)							
Built up	22.5	32.6	45.6	39.6	1.2	11.0	27.3
Crop land	32.2	7.5	6.5	11.3	9.6	12.9	20.5
Dence forest	16.0	28.9	25.1	27.2	26.3	51.7	23.2
Open Forest	4.7	11.5	1.5	0.3	10.3	11.1	5.7
Plantation crops	5.0	0.2	2.4	0.1	0.1	4.9	3.5
Shifting Cultivation*	0.3	2.8	3.3	9.1	0.0	2.4	2.8
Snow covered	0.0	0.0	0.0	0.0	36.7	0.0	0.02
Waste/grassland	8.0	14.6	14.0	11.2	14.9	4.9	10.3
Water bodies	11.2	1.9	1.5	1.2	0.8	1.1	6.5

*Current

Assam has significant area (11.2%) under water bodies while in all the remaining 5 states, area under water bodies is less than 2%. Taking all into account the six NE states with a geographical area of 15.61 Mha, maximum area is under settlement (urban + rural: 27.3%) followed by dense forest (23.2%), crop land (20.5%), grass/wasteland (10.3%), water bodies (6.5%) and open forest (5.7%). Other landuses (Plantation, shifting cultivation and snow covered) occupied 6.4% TGA.

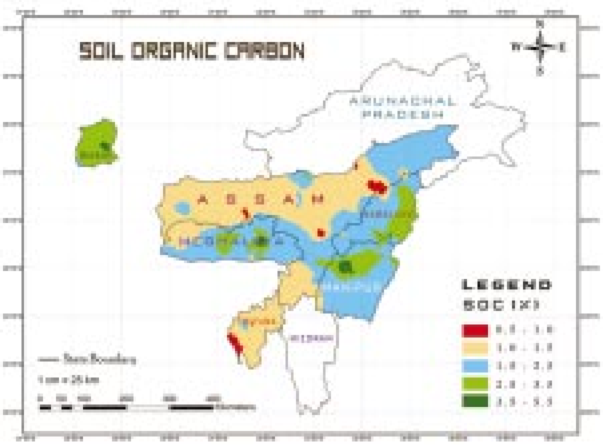
GIS mapping of spatial distribution of Soil organic carbon content across NE Region

The wide variability in spatial distribution of SOC content at surface layer (14.6-18.6 cm) covering both arable and non-arable lands was depicted by spatial maps of SOC content (prepared in GIS domain) (Map 2). Considering the variability of SOC contents in absolute values at spatial scale, we categorized SOC content into five classes' ranged from 0.5% to as high as 5.5% across the six states of NER (Table 4). Of the total geographical area (TGA) of 15.61 M ha covering six states of NE region (including both arable and non-arable lands), SOC content was more than 1% in 98% of TGA while in 57.68% of the area, SOC content was more than 1.5%. Among the N.E states, Sikkim had the highest percentage of TGA (>93%) under high SOC content (2.5 to 3.5%) followed by Nagaland (33.3%) and Manipur (21.8%) (Table 4). More than forty percent area (43.25% of 15.61 Mha) in NER falls under intermediate category of SOC content: 1.5-2.5% and this class (SOC-1.5-2.5%) dominates three states of NER, namely Manipur (71.63% TGA), Meghalaya (62.86% TGA) and Nagaland (61.56 % of TGA). Very high organic carbon content of 3.5-5.5% were recorded only in marginal areas of Sikkim (4.42% area), Manipur (3.64% area), Meghalaya (1.78%) and Nagaland (0.14% area). SOC content in majority of the areas in Meghalaya (78.25% of TGA) falls under medium category (1.5-2.5%) while only 17.16% area recorded SOC content of 2.5-3.5%. Among the NE states, Tripura had the major chunk of TGA (>89%) falls under relatively low SOC content (1.0-1.5%) followed by Assam (62.83%) and

Table 4 Percent geographical area of NE region of India under different classes of SOC (%) content

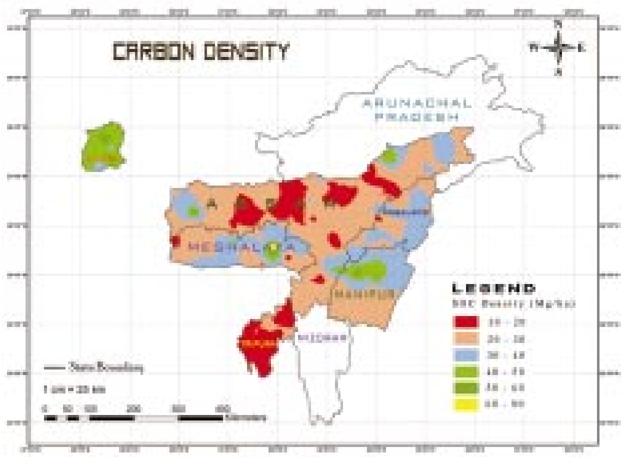
State	Geographical area Mha	SOC content (%) in Percent of total geographical area				
		SOC (0.5 - 1.0)	SOC (1.0-1.5)	SOC (1.5-2.5)	SOC (2.5-3.5)	SOC (3.5-5.5)
Assam	7.790	1.74	62.83	34.59	0.84	…
Manipur	2.218	…	2.93	71.63	21.80	3.64
Meghalaya	2.238	0.07	19.90	62.86	15.39	1.78
Nagaland	1.649	0.81	4.18	61.56	33.32	0.14
Sikkim	0.699	…	…	1.70	93.88	4.42
Tripura	1.017	7.55	89.03	3.42	…	…
Total	15.611	1.45	40.86	43.25	13.44	0.98

Meghalaya (19.9%). SOC content of <1% (0.5-1.0%) was recorded in small areas of Tripura (7.55%), Assam (1.74%) and Nagaland (0.81%) (Table 4). In a nutshell, on the basis of percent TGA having relatively higher SOC content (e”1.5%), the order of sequence stood as Sikkim (100% area) followed by Manipur (97.07%), Nagaland (95.02%), Meghalaya (80.03%), Assam (34.59%) and lastly Tripura (3.42%) (Table 4). Spatial distribution of SOC content across NE region has been depicted in Map 2.



Map 2 Spatial distribution map of SOC content across NE Region of India

Presently prepared spatial map of SOC content is the updated version of previously reported one (Choudhury *et al*., 2011) where an additional 406 geo-referenced locations in addition to previously used 336 locations were used. So, altogether 742 geo-referenced locations were used to prepare the present map. In some of the newly added observations from 406 locations, we recorded a minimum SOC content of 0.5% (Tripura and Assam) and as a result, minimum SOC content recorded was 0.5% contrary to 0.8% or more in the previously reported observation (Choudhury *et al*., 2011).



Map 3 Spatial distribution map of SOC density across NE Region of India

GIS mapping of Soil organic carbon density across NE Region

Soil carbon density of surface layer was estimated from the soil depth, bulk density and the corresponding SOC content for the six states of NE region. On interpolation spatially (using kriging) in GIS environment, wide variability among and within each states of NE region was observed (Map 3). Average SOC density varied from 10 t ha^{-1} to 60 ha^{-1} across NE states, with more than half of the area (52% of TGA: 15.61 Mha) falls under medium category SOC density (20-30 t ha^{-1}) (Table 5). Nearly one fourth of the area (24.30% of TGA) falls under high category SOC density (30-40 t ha^{-1}) while only 8.0 % area falls under very high category SOC density (>40-60 t ha^{-1}). Among the six states, Sikkim had maximum area (81.98%) falls under very high SOC density (40-50 t ha^{-1}) followed by Manipur (13.03 t ha^{-1}) and Nagaland (4.06%). Similarly, Sikkim was the only state having considerable area (>10%) registered very high SOC density (50-60 t ha^{-1}).

Next to Sikkim, Nagaland has 57.5% area falls under SOC density of 30-40 t ha^{-1} while 40.4% area recorded 20-30 t ha^{-1}. Nearly half of the area in Meghalaya (49.51%) registered 20-30 t ha^{-1} while in 42.56% area, SOC density was 30-40 tha^{-1}. Similarly, in Manipur, 49.39% registered 20-30 tha^{-1} and in 36.5% area, SOC density was 30-40 tha^{-1}. Among the NE states, Tripura recorded highest percentage of area (81.8%) under very low category SOC density (10-20 t ha^{-1}). Assam also registered 1/5th of the total area under low SOC density (10-20 tha^{-1}) while in 2/3rd of the area (65.3%), SOC density was 20-30 t ha^{-1} (Table 5).

Table 5 GIS based spatial distribution of different classes of SOC density across NE region of India

State	Geographical area Mha	Carbon density (t ha^{-1}) in percent of total geographical area					
		10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 80
Assam	7.790	19.40	65.31	13.26	1.86	0.17	…
Manipur	2.218	…	49.39	36.51	13.03	1.07	…
Meghalaya	2.238	1.42	49.51	42.56	4.06	1.72	0.73
Nagaland	1.649	1.71	40.43	57.51	0.35	…	…
Sikkim	0.699	…	…	7.17	81.98	10.86	…
Tripura	1.017	81.80	18.20	…	…	…	…
Total	15.611	15.39	52.16	24.30	7.07	0.97	0.13

Among the many reasons responsible for the variation in SOC density across NE region (including within each states), deviation in soil organic carbon content seems to be foremost factor since it reflected a very strong positive correlation (r = +0.68 to +0.86) with SOC density across all the six states of NE region. Again, variation in SOC content is controlled by many factors, of which landuse-land cover transformation and post management practices including agricultural practices plays major role. The significant influence of landuse practices on surface SOC content across NE region was affirmed by Choudhury *et al*. (2011) where they reported that surface soils under grass land and dense forests contain very high SOC content (>2%) compared to settled agriculture including lowland paddy (SOC-1.45-1.69%) as well as shifting cultivation (1.70%). Next to SOC content, it was sampling depth, which also reflected a positive correlation with SOC density (r=+0.32 to +0.67) and then soil bulk density. This was also affirmed from the results revealed in considerable variation of SOC content among the six studied states of NE region, which varied from 1.23% to 2.99% (Tables 2 and 4) compared to marginal variation in sampling depth (14.6 cm to 18.6 cm, Table 3) and soil BD values (0.88 to 1.32 Mg m^{-3}) (Table 3). Variation in parent materials, more particularly particle size distribution (soil separates), climatic factors, more particularly amount and distribution pattern of rainfall in luxuriant growth and regeneration rate of phyto-biomass also exerts considerable influences on SOC content and soil bulk density values. Therefore, integrated effects of host of factors ranging from SOC content to landuse practices resulted in variation of SOC stock-density across NE region of India.

Conclusion

Irrespective of landuse system practices across six states of NE region, SOC content and per unit carbon density of the soils was very high (except Tripura) compared to other parts of the country, although, addition of organic matter or chemical fertilizer either in natural vegetation or in cultivated areas through management intervention were marginal and limited to few pockets only. This may be one of the reasons for supporting low/marginal input intensive traditional agricultural production systems in yielding productivity close to national average and thus helping the resource poor farmers of NE region in food grain and livelihood security. However, alarming rate of deforestation, prevalence of slash and burn agriculture (jhuming) and other faulty landuse practices induced biomass burning of 8.5 million tonnes annually are threatening the very sustainability of soil carbon and soil health *vis-a-vis* agricultural production systems and food security of the region.

Since soil carbon is considered one of the most important keys to soil fertility, productivity and quality, decline in carbon content not only affects sustainability of agricultural ecosystems, but also extremely important in maintaining overall quality of environment as soil contains a significant part of global carbon stock (3.5%). By sequestering of 1 tonne carbon in humus, we can conserve 83.3 kg N, 20 kg P and 14.3 kg S nutrients per hectare. Thus, carbon management is the key to environment management and sustainability of soil health *vis-a-vis* agricultural productivity. In this context, effective landuse planning, periodic replenishment of soil nutrients in cultivated areas, improvement in jhum cultivation, soil and water conservation etc. can substantially mitigate the risk of land degradation and its adverse consequences on soil health including carbon status.

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Impact of Land Use Management on Soil Organic Carbon Dynamics

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Introduction

Cereal production in India increased from 50 million tonnes in 1947 to 219 million tonnes in 2000, though the requirement is expected to increase to 300 million tonnes by 2050. But there are severe problems of degradation of soil and water resources leading to reduction in productivity, input use efficiency (e.g., fertilizer, irrigation), pollution of surface and ground waters, and emission of greenhouse gases (GHGs) from terrestrial and aquatic ecosystems into the atmosphere. Soil organic carbon play multifunctional role to improve this degradation. Majority of carbon is held in the form of soil organic carbon, having a major influence on soil structure, water holding capacity, cation exchange capacity, the soils ability to form complexes with metal ions to store nutrients, improve productivity, minimize soil erosion etc. This organic carbon is highly sensitive to changes due to land use and management practices such as increased tillage, cropping systems, fertilization etc.

Sink of carbon from atmosphere to either plant or soil or directly from atmosphere into soil is called as soil carbon sequestration. Excluding carbonate rocks (inorganic carbon path), the soil represents the largest terrestrial stock of carbon, holding 1500 Pg (1Pg = 10^{15}g), which is approximately twice the amount held in the atmosphere and three times the amount held in the terrestrial vegetation. Soil inorganic carbon (SIC) pool contains 750 -950 Pg C. Terrestrial vegetation is reported to contain 600 Pg C. Atmospheric concentration of carbon dioxide and other green house gases is changing rapidly because of anthropogenic activities including fossil fuel combustion, deforestation, biomass burning, cement manufacturing, drainage of wetlands and soil cultivation. The current level of carbon dioxide concentration in the atmosphere which was at 370 ppm in 2004, is increasing at the rate of 1.5 ppm per year or 3.3 Pg C per year. Researchers predicted that unless drastic measures are taken to reduce net emission of carbon dioxide, atmospheric carbon dioxide may increase to 800 to 1000 ppm by the end of 21st century. Climatic sensitivity to atmospheric enrichment of carbon dioxide may be 1.5 to 4.5^{0}C increase in mean global temperature, with attendant increase in sea level.

About 20 % of the earth's land area is used for growing crops and thus farming practices have a major influence on C storage in the soil and its release into the atmosphere as CO_2. Within cropping/farming system, the equilibrium levels of soil organic carbon (SOC) can be related linearly to the amount of crop residue returned/applied to soil. The rate of accumulation of SOC depends on the extent to which the soil is already filled by SOC i.e., the size and capacity of the reservoir. Mechanical disturbance of soil by tillage increases decomposition rate of SOC. Practices, which increase residue, and/or plant growth result in enhancing SOC sequestration. The beneficial effect of SOC is more than improving soil quality and fertility.

Total geographical area of India is 328.7 million hectares (m ha) or about 2.5% of the total land area of the world (Table 1). It is home to 1.1 billion or 16% of the world population. India is the second most populous country in the world. Principal land uses include 161.8 m ha of arable land (11.8% of the world) of which 57.0 m ha (21.3% of the world) is irrigated, 68.5 m ha of forest and woodland (1.6% of the world), 11.05 m ha of permanent pasture (0.3% of the world) and 7.95 m ha of permanent crops (6.0% of the world). The large land base, similar to that of the U.S.A. and China or Australia, has a potential to sequester C and enhance productivity while improving environmental quality. The Green Revolution of the 1970s needs to be revisited to enhance production once again and to address environmental issues of the 21st century including climate change. Thus, we need to understand how land use and management practices such as fertilization, tillage, cropping systems etc. can potentially enhance SOC storage and improve environmental quality. The C-sequestration mechanism, total carbon stocks in Indian soils, possible ways to enhance SOC have been discussed in this chapter.

Table 1 The land use (m ha) in India and the world in 1999

Land use	World	India
Total area	13,414.2	328.7
Land area	13,050.5	2973.0
Permanent crops	132.4	7.95
Permanent pasture	3,489.8	11.05
Forest and woodland	4,172.4	68.5
Agricultural area	4, 961.3	180.8
Arable land	1,369.1	161.8
Irrigated land	267.7	57.0

SOC potential in different soil orders of India

Soils of India have been categorized as low in organic carbon and nitrogen although there are many variations like genetic, morphological, physical, chemical, and biological characteristics, associated with changing physiography, climate and vegetation. If we compare the isothermal and isohyets of India and North America, the organic carbon reserves of Indian soils, either virgin or cultivated, are higher, but they are lower than those of Central America (Jenny and Raychaudhury, 1960). The observed losses in soil organic carbon from managed ecosystems are greater in semiarid environments than in the humid low lands (Table 2). This indicates that a large portion of organic carbon under natural vegetation of arid and semiarid region is less recalcitrant than humid tropical soils. A study indicated that the rate of decline in total organic carbon in the agro-ecosystem reduced two times faster than that of the soil carbon storage in the sub humid woodland forest and plantations. Long-

Table 2 Influence of elevation, precipitation and temperature on organic carbon status under cultivated and forest lands of India

Location	Elevation (m)	Precipitation (cm)	Temperature (ºC)	Carbon (%)	
				Cultivated	Native
Northwest India					
IGP		25-51	25	0.3±0.033	0.59±0.211
		53-76	24-26	0.45±0.038	0.91±0.113
		79-102	23-25	0.55±0.037	-
		104-127	23-24	0.55±0.049	1.40±0.157
		130-152	23	0.35±0.059	1.24±0.297
Northwest Himalayan					
Dehra Dun-Mussouri	457-1067	216-224	23-20	1.44±0.145	1.81±0.270
Shimla	1067-1524	216-224	20-17	2.01	3.53
	1524-2134	216-224	17-14	3.37±0.365	3.99±0.346
	2195	155	13	2.91±0.386	4.48±0.258
Northwest India					
Sriganganagar		25	25	0.33	-
Meerut		74	24	0.50	-
Biharigarh		122	24	0.51	-
Mohan		145	23	2.64	-
Northeast India					
Tista- Brahmaputra Plains		249-389	24	1.37±0.119	2.32±0.160
Assam Hill & Valleys		129-1080	24-17	1.26±0.182	1.56±0.166
Himalayan Ranges					
	610-1311	300-315	21-17	3.18±0.221	4.82
	914-1158	218	19-18	2.23±0.219	-
	1524-2316	295-330	16-12	3.58±0.315	6.63±0.695
Southeast India					
Madurai-Kodaikanal Mountain Transect	610	104	26	0.32±0.0025	1.73
West coast of India					
Dry coastal region		56-472	27	0.74±0.134	
Humid coastal area	108-223	27	1.89±0.272	1.86±0.212	
Deccan Plateau and adjacent mountains					
Mysore-Bangalore area	79-86	25-23	0.52±0.036	1.68±0.230	
Nagpur-Bellary		51-124	27	0.55±0.124	1.09±0.170
Western Ghats-Nilgiri Hills		130-917	24	1.25	2.59

(Source: Jenny and Raychaudhury, 1960)

term effect of exhaustive soil management practices and the climate on the organic carbon and nitrogen reserves of Indian soils indicate that differentiation of organic C, total N and C/N ratio, is a function of temperature, rainfall and cultivation.

About 40% of the cultivated soils of the Indo-Gangetic alluvium are calcareous and more precisely, they contain C as carbonates. Initially, the geographic distribution of these calcareous bodies was conditioned by the flow patterns of the rivers, which traverse and erode calcareous strata in the Himalayan mountains. But in due course of time, with the increase in precipitation from 127 to 152 cm, the portion of calcareous soils declined by 20%. These large groups of cultivated, alluvial soils are richer in soil organic carbon than non-calcareous soils. This phenomenon may be meaningful if textural and climatic variables are simultaneously taken into account. In the drier section of the Indo-Gangetic Plains (IGP), the areas of natural vegetation are thin. They consist of thorny volunteer shrubs on drifting sand dunes and patches of temporarily abandoned land, and of clumps of wild grasses. The native vegetation comprises small *Acacias* and leguminous broad leaf trees intermingled with large specimens of *Euphoria* type bushes. The means of the combined vegetation type show a striking relation to elevation of northwest Himalayan soil. The soils above 1524 m are twice as rich in organic carbon as compared to the soils below 1067 m. The surface layer (0-20 cm) is very dark and rich in carbon, and the subsoil is distinctly low in organic carbon with no visible signs of fossilization.

Under natural vegetation, organic carbon may reach a near-steady state after 500 to 1000 years. Depletion of soil organic carbon under cultivated field was 23 to 48% of original value. It is documented that the agricultural soils of northwest India exclusive of the Himalayas have lost about one half to two thirds of their original organic carbon content. Northeast India consists of Tista-Brahmaputra plains, Assam Hill and valleys, and lesser Himalayan regions. Tista- Brahmaputra plains consist of relatively recent deposits which have been mapped as new alluvium and occasionally older, dissipated terraces which have weathered into reddish soils. The mean annual precipitation varies from 249 - 389, 129- 1080 and 219 - 338 cm under Tista- Brahmaputra plains, Assam Hill and valleys, and lesser Himalayan ranges, respectively. If the mean annual temperatures of Himalayan range are plotted against elevation, a nearly perfect straight line results with a negative gradient of 0.062ºC per 30.5 m. The organic carbon values of these soils are two to three times higher than those of the cultivated soils of the Indo-Gangtic alluvium, presumably because of higher rainfall (254-356 cm) and finer textures of the soils. For cultivated soils, the mean percentage value for carbon of Assam Hill and valleys is 1.26 ± 0.128. In the regions of southeast India, the mean carbon content of cultivated soils of foot hills and plains is about 0.45%, and the values are nearly identical with those from the soils of the Indo-Gangetic plains having corresponding rainfall. The soils are covered with native vegetation predominantly consisting of *Acacias*, *Euphorbia*, thorny shrubs, patches of poor stands of grass, and bare spots largely unsuitable for agricultural production. The mean organic carbon content is $0.76 \pm 0.076\%$. Organic carbon increased with increase in elevation under native vegetation and in cultivated fields of Madurai-Kodaikanal mountain sector.

The regions of the west coast of India, called Malabar and Kanara coast section, are laterite plateaus carrying bare iron stone crusts of panzer-like hardness and impenetrability. Along the entire dry coastal region, the range of annual rainfall enormously increase from 56 to 472 cm and the mean annual temperature is about 27ºC. The average organic carbon content is 0.74±0.134. The mean organic carbon percent in non-paddy soils of humid coastal regions is about 0.92±0.155, which is significantly lower than that in paddy soils (SOC=1.89±0.272). The organic carbon content in cultivated land is approximately half of the native vegetation. The data in table 3 shows a decline in SOC concentration of cultivated soils by 30 to 60% compared with the antecedent level in undisturbed ecosystems.

Table 3 Depletion of soil organic carbon content of cultivated soils compared with that in undisturbed soils (adopted from Jenny and Raychaudhary, 1960; Swarup *et al*., 2000)

Region	SOC content (%)		Percent reduction (%)
	Cultivated ($g\ kg^{-1}$)	Native ($g\ kg^{-1}$)	
1. Northwest India			
Indo-Gangetic Plains	4.2 ± 0.9	104 ± 3.6	59.6
Northwest Himalaya	24.3 ± 8.7	34.5 ± 11.6	29.6
2. Northeast India	23.2 ± 10.4	38.3 ± 23.3	39.4
3. Southeast India	29.6 ± 30. 1	43.7 ± 23.4	32.3
4. West coast	13.2 ± 8.1	18.6 ± 2.1	29.1
5. Deccan Plateau	7.7 ± 4.1	17.9 ± 7.6	57.0

Table 4 Organic carbon stock in different soil orders of India

Soil orders	Organic carbon (0-30 cm depth) (Pg)	Percent of total carbon stock in India
Entisols	1.36	6.5
Inceptisols	4.67	22.2
Vertisols	2.62	12.5
Aridisols	7.67	36.5
Mollisols	0.12	0.6
Alfisols	4.22	20.0
Ultisols	0.14	0.8
Oxisols	0.19	0.9
Total	20.99	100

Sources: Velayutham *et al*. (2000)

The SOC stocks for India in terms of each soil order is estimated at 0-30 cm depths and such quantitative data reflect the kinds of soil with different amount of organic carbon (Table 4). Indian soils are commonly classed as Inceptisols, which contribute about 22% of the total SOC stock. Entisols contribute nearly 7% of the total SOC stock of Indian soils. Vertisols are extensive in the central and southern parts of India and contribute about 13% of the total SOC. Aridisols are in general poor in organic carbon due to their high rate of decomposition, low rate of plant growth. However, a few arid soils belonging to cold (Typic Camoryorthids), hot (Typic Camorthids/ Natragids/Calciortids) and arid ecosystem contribute about 37% of the total SOC stock. The Indian Mollisols contribute less than 1% of the total SOC stocks due to the fact that only a small portion of geographical area of the country is covered by these soils. Most of Alfisols occur in sub-humid to humid regions of the country and contribute about 20% of the total SOC stocks. Oxisols contribute less than 1% of the total SOC stock. Poor accumulation of SOC in Oxisols is due to greater decomposition in tropical humid regions.

Factors affecting SOC restoration

Soil organic carbon equilibrium is governed by a number of interacting factors such as temperature, moisture, texture, quality and quantity of organic matter applied, soil type, soil tillage and cropping systems. Maintenance of soil organic carbon is important for productivity and sustainability. Other important benefits of SOC in low-input agro-ecosystems are retention and storage of nutrients, increased buffering capacity, better soil aggregation, improved moisture retention, increased cation exchange capacity, and greater chelating. Addition of organic carbon improves soil structure, texture and tilth, activates a significant portion of inherent microorganisms, and reduces the toxic effects of pesticides.

A. Soil type

Soil type is one of the important factors that regulate organic carbon status of the soil. The soils of India broadly fall into five major groups *viz*., alluvium derived soils (Inceptisol and Entisol: 74.3 million ha), black soils (Vertisol: 73.2 million ha), red, yellow and laterite soils (Alfisol and Oxisol: 87.6 million ha), and soils of desert regions (Aridisol: 28.7 million ha). The extent of clay aggregation is a direct controlling factor in organic carbon dynamics. Organic carbon content increases with clay content under desert, red, alluvial, laterite and literitic soil, saline and black soil, except mountain and forest soil which had the highest organic carbon at 34.5% clay, possibly due to continuous deposition of unhumified organic carbon in these soils. Irrespective of climatic factors, increased amounts of sand, coarse loam, or gravelly sandy loam decrease the organic carbon content which is due to less microbial proliferation and aggregation for carbon restoration.

B. Rainfall and temperature

Temperature and rainfall exert significant influence on the decomposition of soil organic carbon and crop residues. Rise in the mean annual temperature reduces the level of SOC of cultivated soil in the humid region. Higher temperature activates the soil microbial population to a greater extent then plant growth. In temperate climates, the soils are several times richer in organic carbon than warmer climate (Table 5). High rainfall and low temperature are conducive to accumulation of organic carbon in soils while high temperature and low rainfall decrease it.

C. Rate and method of application of crop residues, fertilizers and manure

The importance of organic manuring in Indian agriculture has been known since ancient times. Whether the organic matter status of soils can be built up under tropical conditions of India has been often debated. The rate of organic matter application to soils varies according to the crop, climate, quantity and quality of organic matter (Table 6). Traditionally, most of

Table 5 Effect of temperature on soil organic carbon within selected moisture belts (Isohyets) in India

Areas	Mean annual temperature (ºC)	Organic carbon (%)
Dry region	23-24	0.5±0.028
Indo-Gangetic alluvium		
Jaipur Hills, Mysore plateau		
Bhavanagar, Kanya Kumari, Bellary	27-29	0.54±0.075
Semi-humid region		
Mysore plateau	23-24	0.55±0.054
Southeast coast	29	0.30±0.031
Humid region		
1. Cultivated soils		
Shimla	7	2.91±0.386
Upper Mussoorie	7-8	3.37±0.365
Dehra Dun-Rajpur	8-11	1.44±0.145
Assam	12	1.26±0.182
2. Forest soils		
Shimla	7	4.48±0.258
Upper Mussoorie	7-8	3.99±0.346
Dehra Dun-Rajpur	8-11	1.81±0.270
Assam	12	1.56±0.166
Per humid region		
1. Cultivated soils		
Darjeeling	6-8	3.58±0.315
Tista-Brahmaputra plains	12	1.35±0.119
Malabar coast	14	2.06±0.492
2. Forest soils		
Darjeeling	6-8	6.63±0.695
Malabar coast	8	2.85±0.352
Tista-Brahmaputra plains	12	2.32±0.160
Malabar coast	14	2.46±0.354

(Source: Jenny and Raychaudhury, 1960)

the farmers unload manure in small piles or heaps and leave it for 5 to 6 months before it is spread on the fields. During this process, plant nutrients are lost due to exposure to the sun and rain by volatilization or leaching. To derive the maximum benefit, organic materials should be applied during land preparation and incorporated into the soil with adequate moisture about two to three weeks before sowing the crop. Results on the impact of diverse organic materials on soil organic carbon are provided in table 6. From different observations it may be concluded that continuous application of FYM and green manure substantially improved the SOC under different soils and cropping systems. Under tropical and subtropical climatic conditions, applications are necessary to obtain good results. The rate of organic matter application to soils will be determined by the amount of nutrients that can be utilized by the crops. About 25 t ha^{-1} of FYM is recommended under intensive irrigated cropping conditions for sugarcane (*Saccharum officinarum* L.), potato (*Solanum tuberosum* L.) and rice (*Oryza sativa* L.), 10 to15 t ha^{-1} for irrigated or rain fed crops where potential rainfall is medium to heavy (about 125 cm yr^{-1}) and 5 to 7 t ha^{-1} in dry areas where the mean annual rainfall is about 25 cm. In dry land farming areas, application of 25 t ha^{-1} of compost can give significant increase in crop-yield.

Table 6 Effect of farmyard and green manure on soil organic carbon under different land use systems

Land use	Treatment	t ha^{-1}	Organic C (%)	References
Alluvial maize-wheat	Control	-	0.51	Biswas *et al*. (1971)
(15 years)	FYM	69.7	2.49	
Medium black cotton-	Control	-	0.56	Khiani & More (1984)
Sorghum (45 years)	FYM	6.2	1.14	
Black soil Ragee-	Control	-	0.30	Mathan *et al*. (1978)
Cowpea-maize (3years)	FYM	25	0.64	
Red soil rice-rice	Control	-	0.43	Hegde (1996)
(10 years)	50% from inorganic + 50% through green manure (*Sesbania aculeate*)	-	0.90	
Sodic soil rice-wheat	Control	-	0.44	Manna *et al*. (1996)
(3 years)	FYM	16	0.54	
Sodic soil rice-wheat	Fallow-rice-wheat	-	0.23	Swarup (1998)
(7 years)	Green manure (*Sesbania aculeate*)-rice-wheat	-	0.37	

D. Tillage and residue management

The SOC losses can be reduced by several tillage options such as zero tillage, reduced tillage, stubble mulching and conventional ploughing. In a 3 year field experiment, the effects of types of tillage operations and continuous addition of organic matter through use of naturally occurring wild shrub (*Lantana camera* L.) was tested. It was observed that application of *Lantana camera* L.@ 10 t ha^{-1} yr^{-1} improved soil physical properties and organic carbon content. Mulch conservation tillage treatments favorably moderated the hydrothermal regimes for growing of crops. In a 45-years long-term study, effect of green manure and tillage operations on FYM, organic carbon content and crop productivity in cotton sorghum system was evaluated (Table 7). In another study, residue management as surface mulch and reduced tillage provided a congenial environment for native micro-flora and fauna which significantly improved SOC. In alluvial soil, application of residue mulches or compost often improves organic carbon.

Table 7 Physico-chemical properties of the soil (0-20 cm depth) and mean yield of cotton and sorghum grown in rotation under rainfed condition for 45 years

Treatment	Organic Matter (%)	Total Nitrogen (%)	Available nutrients ($kg\ ha^{-1}$)			Mean seed yield of cotton ($t\ ha^{-1}$)	Mean grain yield of sorghum ($t\ ha^{-1}$)
			N	P	K		
HM	1.16	0.061	93.8	13.76	320	3.28	9.37
PM	1.13	0.059	90.7	15.24	345	2.98	12.30
H	0.59	0.047	77.8	10.48	283	1.44	7.15
P	0.52	0.045	72.8	11.68	267	1.66	9.73
LSD at 5%	0.05	0.017	2.7	0.80	6.66	0.50	3.07
Tillage							
Harrowing	0.9	0.054	85.4	12.12	321	2.36	8.26
Ploughing	0.8	0.052	81.8	13.40	321	2.26	11.01
LSD at 5%	NS	NS	2.2	0.56	4.7	NS	2.18
Manuring							
FYM	1.14	0.060	92.3	14.50	333	3.09	10.84
No manure	0.56	0.046	75.0	11.08	290	1.53	8.44
LSD at 5%	0.04	0.012	2.26	0.56	4.7	0.35	2.18

Source: Khiani and More (1984), HM = Shallow tillage, harrowing up to 8-10 cm depth by Deccan blade harrow and manuring @ 6.2 t ha^{-1} of FYM; PM = Deep tilling, ploughing up to 18-20 cm by iron plough (Kirloskar) and application of FYM at 6.2 t ha^{-1}; H = Shallow tillage, harrowing only up to 8-10 cm depth with Deccan blade harrow and P = Deep tillage ploughing upto 18-20 cm with iron plough, NS = Not significant.

In semiarid regions of India, utilizing the wastes through composts, amended with minerals such as rock phosphate, pyrites, and N application have been recognized for improving the crop yields and SOC. In a six years study on Alfisols, it was observed that continuous application of crop residues @ 4 t ha^{-1} increased SOC from the initial value of 0.6 to 0.9% (Hadimani *et al*., 1982). Concentrated organic manures such as oilcake are no longer recommended in India because of rapid carbon dioxide evolution during decomposition in soil, which retards root respiration particularly of transplanted rice. However, application of oilcake, decomposed for 10-15 days before application has been found to be effective in terms of crop establishments. Incorporation of wheat straw @ 6 t ha^{-1} in rice and @ 12 t ha^{-1} in wheat in sandy loam soil increased SOC by about 8%. Beneficial effect of FYM @ 10 to 15 t ha^{-1} in improving organic carbon over control, N, NP, and fertilizer have been reported on Vertic Ustochrept, Chromstert and Haplustert (Swarup, 1998).

The practice of green manuring as catch crop between harvest of wheat and planting of rice is not popular among the Indian farmers mainly due to (i) non- availability of water, and (ii) farmers' belief that they loose one crop during the growing season. However, growing summer mung could be realistic to the farmers because of its dual function (i) increase in SOC and (ii) highly profitable yield.

Soil organic pools and dynamics

So far literature on soil organic matter (SOM) changes in rainfed, semiarid and sub-humid regions of India did not throw much light on the carbon functional pools, which are highly sensitive indicator of soil fertility and productivity. The distribution of soil organic matter into following five functional pools may be made for its true representation.

Structural litter fraction: This consists of straw, wood, stems and related plant parts. The C:N ratio varies around 150:1. These are high in lignin content.

Metabolic pool fraction: It comprises plant leaves, bark, flower, fruits and animal manure. The C:N ratio ranges from 10 to 25. This fraction gives up mineral nitrogen when it is decomposed.

Active pool of soil carbon: This is microbial biomass and their metabolites. The C:N ratio is around 5 to 15. This fraction gives up mineral nutrients and it gives life to the soil. Besides SMBC, light fraction of organic matter, water soluble carbon and water soluble carbohydrates are also active pools of organic matter.

Slow decomposable soil fraction: This fraction is comparable to nature of composting materials having C:N ratio around 20:1. It makes temporary stable humus in soil, which is slowly decomposable.

Passive soil organic fraction: This is the highly recalcitrant organic matter with C:N ratio of 7:1 to 9:1. It is resistant to oxidation and is not readily involved in dynamic equilibrium with other types of organic fractions in soil. The specific relationship of management practices and biologically active soil organic matter with soil process is not well characterized. The structure of SOC sub-model is illustrated in Century Model (Fig 1) (Parton *et al*., 1987).

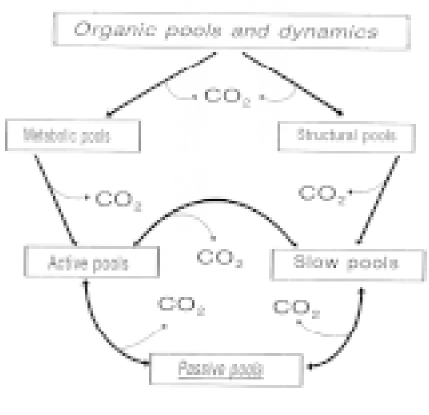

Fig 1 Century Model

This model includes respiration C losses associated with dynamics of organic pools. Similarly, the N- sub models have the same basic structure of SOM and also include the flow of nutrients in different mineral form. Moreover, SOC turnover is dependent on soil moisture, radiation, temperature, cropping, rooting, plant residue etc. Combined effect of all these factors on the dynamics of SOM is not yet established in tropics. Studies therefore, need to be conducted to develop a model of SOM for rainfed rice-based cropping systems which will include different parameters such as physical properties of soil, nutrient status, light fraction of SOC, hot water soluble carbon, SMBC, activity of enzymes etc. Such model may be of great practical importance from management point of view and as an indicator of soil quality.

Mechanisms of C- sequestration

Soil organic matter (SOM) is protected against decomposition by various mechanisms. Soil organic matter can be: (1) physically stabilized, or protected from decomposition through microaggregation, (2) intimate association with silt and clay particles, and (3) biochemically stabilized through the formation of recalcitrant SOM compounds. In addition to this each SOM pool changes in land management by which SOM compounds undergo protection and release. The characteristics and responses to changes in land use management are described for the light fraction (LF) and particulate organic matter (POM-C). If LF and POM-C is not occluded within microaggregates (53-250 µm) then such carbon is unprotected. Physicochemical characteristics inherent to soils define the maximum protective capacity of these pools, which limits increases in SOM (i.e., C sequestration) with increased organic residue inputs. Some long-term experiments showed that little or no increase in soil C content was observed in imbalanced application of N or NP fertilizer under different soil and cropping systems in India (Manna *et al*., 2005a).

Chemical stabilization: silt and clay-protected SOM

The protection of SOM by silt and clay particles is well established. Basically the retention of specific microbial products (amino sugars such as glucosamine, muramic acid etc.) chemically protect the C that is associated with primary organo-mineral complex. Many researchers observed that mineral associated carbon (MAC) with 20 µm size classes of silt +clay have higher potential of C stabilization capacity than sand size fraction of C associated with macro-aggregates (53-2000 µm). We observed that mineral associated carbon having <53 µm size classes of silt+clay retained greater amount of carbon as compared to LF and POM-C associated with macro-aggregates (Manna *et al*., 2005b and 2007b). Further, we observed that MAC was greater in NPK+FYM treatment (Table 8) in Inceptisols compared to Alfisol and Vertisol.

Physically protected SOM

Physical protection by aggregates is indicated by the positive influence of aggregation on the accumulation of SOM. The physical protection exerted by macro and micro-aggregates on particulate organic matter carbon (POM-C) is attributed to (1) the compartmentalization of substrate and microbial mass, (2) reduced diffusion of oxygen into aggregates, which leads to reduced activity within the aggregates, and (3) compartmentalization of microbial biomass and microbial activities. Many studies have documented positive influence of aggregation on the accumulation of SOM under different soils and cropping systems (Hati *et al*., 2008; Manna *et al*., 2005b; Manna *et al*., 2007a; Manna *et al*., 2007b). Cultivation

Table 8 Long-term effect of manure and fertilizer application on soil organic carbon pools under Inceptisol (Rice-Wheat-Jute, R-W-J) and Vertisols (Sorghum-Wheat, S-W) and Alfisols (Soybean-Wheat, S-W) system at 0-15 cm soil depth

Locations	Treatments	MAC ($g\,kg^{-1}$)	LF-C ($mg\,kg^{-1}$)	AHC ($mg\,kg^{-1}$)	SOC ($g\,kg^{-1}$)	% POM in SOC
Barrackpore	Control	4.5	61	526	5.4	10.6
Inceptisol (R-W-J)	N	4.7	91	580	5.7	16.5
	NP	4.8	99	609	6.3	22.4
	NPK	5.8	120	689	7.4	20.0
	NPK+FYM	5.5	212	845	7.9	27.0
Akola	Control	3.1	49	462	3.6	10.3
Vertisols (S-W)	N	3.9	98	590	5.2	23.3
	NP	4.3	101	620	5.6	26.7
	NPK	4.1	131	725	6.1	30.1
	NPK+FYM	3.9	282	840	7.1	39.7
Ranchi	Control	3.3	-	328	3.5	10.3
Alfisols (S-W)	N	3.6	-	368	3.4	9.8
	NP	3.3	-	442	4.2	14.7
	NPK	3.1	-	466	4.5	26.7
	NKP+FYM	3.2	-	517	4.7	31.2

MAC: mineral associate carbon; LF-C: light fraction carbon; AHC: acid hydrolysable carbohydrates; SOC: soil organic carbon; POM: particulate organic matter. (Source: Manna *et al*., 2005b; 2007a; 2007b)

causes release of C by breaking up the aggregate structures, thereby increasing availability of C. More specifically, cultivation leads to loss of C-rich macro-aggregates and an increase of C-depleted micro-aggregates (Hati *et al*., 2008).

In general, the occluded light fraction had higher C and N concentrations than the free light fraction and contained more alkyl C (i.e., long chains of C compounds such as fatty acids, lipids, cutin acids, proteins and peptides) and less O-alkyl C (e.g., carbohydrates and polysaccharides). During the transformation of free light fraction into intra-aggregate light fraction, there is selective decomposition of easily decomposable carbohydrates (i.e., O-alkyl C) and preservation of recalcitrant long-chained C (i.e., alkyl C) and that cultivation decreased the O-alkyl content of the occluded SOM. This difference is the result of continuous disruption of aggregates, which leads to faster mineralization of SOM and preferential loss of readily available-C (Manna *et al*., 2005b). Hence, the enhanced protection of SOM by aggregates in less disturbed soil results in accumulation of more labile C than would be maintained in a disturbed soil. Other studies also indicated that the macro-aggregate (>250 μm) structure exerts minimal amount of physical protection whereas SOM is protected from decomposition in free micro-aggregates (<250 μm) and in micro-aggregates within macro-aggregates (Six *et al*., 2000). They reported that C mineralization increased when macro-aggregates are crushed, but the increase in mineralization accounted for only 1-2% of the C content of the macro-aggregates. These studies clearly indicate that C stabilization is greater within free micro-aggregates than within macro-aggregates. The general characteristics of LF are: (i) consists of plant residues in various stages of decomposition; (ii) presence of charcoal; (iii) contain various sugars (mannose + galactose/Arabinose + Xylose); (iv) high O-alkyl content; (v) high C/N ratio; (vi) low net N mineralization potential; (vii) contain labile SOM pool (viii) high lignin content; in high phenyl propenoic acid/benzoic acid ratio.

We have studied LF and POM from >2000 µm size classes from three soil types under long-term fertilizers experiment. It was observed that long–term application of manure and fertilizers improved the LF-C, which varied from 1.1 to 2.7 % of SOC in Inceptisols and 1.3 to 3.9 % of SOC in Vertisols (Table 8). POM-C varied from 10.6 to 27 % of SOC in Inceptisols, 10.3 to 39.7 % of SOC in Vertisols and 10.3 to 31.2 % of SOC in Alfisols. The acid hydrolysable carbohydrates were substantially improved in the NPK+FYM treatment compared to inorganic fertilizer application in all these three type of soils.

Biochemically protected SOM

Biochemical protection of SOM occurs due to the complex chemical composition of the organic materials. This complex chemical composition can be an inherent property of the plant material (lignin, hemicelluloses, etc. referred to as residue quality) or be attained during decomposition through the condensation and complexation of decompositing residues, rendering them more resistance to subsequent decomposition. Therefore, this pool is stabilized by its inherent or acquired biochemical resistance to decomposition. This pool is referred to as the ‘passive’ SOM pool (Parton *et al*., 1987) and its size has been equated with the non-hydrolyzable fraction. Several studies have found that the non-hydrolyzable fraction in temperate soils includes very old C and acid hydrolysis removes proteins, nucleic acids, and polysaccharides (Schnitzer and Khan, 1972) which are believed to be chemically more labile than other C compounds, such as aromatic humified components and wax-derived long chain aliphatic compound.

Soil organisms mediated C- sequestration

Microorganisms and their activities are the main mediators of C-sequestration. The plant residues decomposition products undergo chemical and physical transformation in soil. However, the relative contribution of these two mechanisms to the processes of C-sequestration in soil is still unclear. Many studies have indicated that arbuscular mycorrhizal (AM) fungi produce glomaline by hyphae which is very stable at high temperature (>120^{o}C) and hydrophobic characteristics of glomaline might be involved in stabilization of soil aggregates and C- sequestration. We examined the long-term effect of manures and fertilizer application on total glomaline content in Vertisols under soybean-wheat system (Table 9). After 39 years of cultivation, it was observed that application of NPK with FYM improved total glomaline (141mg kg^{-1}) content as compared to imbalanced fertilizer application (39 to 41 mg kg^{-1}).

Organic carbon potential under different land use and land management systems

Alternate land use systems, *viz*. agro-forestry, agro-horticulture, and agri-silviculture, are more effective for SOC restoration as compared to sole cropping (Table 10). In the northeast hill states India, all the above three land use system are existing that reduce soil erosion and SOC loss considerably. In a 5 year study, organic carbon content was about double in agro-horticultural and agri-forestry systems as compared to shifting cultivation (Table 11).

Table 9 Effect of long term fertilizer and manure application on total glomaline content

Treatments	Total Glomaline content (mg kg^{-1})
Control	29.4
N	38.7
NP	41.6
NPK	132
NPK+FYM	141

Table 10 Organic carbon in soil after six years of plantation in different land use options

System	Organic C (%)	
	0-15 cm	15-30 cm
Sole cropping	0.42	0.37
Agri- forestry	0.71	0.73
Agri- horticulture	0.73	0.74
Agri-silviculture	0.38	0.56

(Source: Das and Itnal, 1994)

Table 11 Comparison of watershed based alternative land use systems (mean of 5 year)

Land use	Soil and water conservation manure	Soil loss (t ha^{-1})	Organic carbon loss ($kg^{-1}ha^{-1}yr^{-1}$)
Shifting cultivation (maize, tapioca, vegetables) (mono-cropping)	—	40.9	70.3
Agriculture in 1/3 lower portion, intercropping field crops with horticulture in upper 2/3 (agri-horticulture) portion	Partial terrace or half-moon terrace	2.6	35.1
Agriculture in entire area [rice on lower terrace, maize and tapioca on higher terrace followed by black gram and mustard (double cropping)]	Full bench terrace	2.1	30.8
Agriculture in the entire area	Contour bund	16.0	260.8

Adopted from: Munda *et al*. (1996)

Inclusion of trees in the agroforestry systems enables synchronized release of nutrients from decaying plant residues that matches with the requirement for nutrient uptake by the crops. In a 5-year study, Gupta (1995) reported that soil organic carbon increased from the initial value of 0.44 to 0.95, 0.94, 0.88, 0.80 and 0.76 percent under *Dalbergia sissoo*, *Pongamia sp, Leucaena leucocephala, Acacia nilotica* and *Dalbergia latifolia,* respectively. In a silvipastoral system of land management, improved pasture species were grown along with tree species. The selection of tree species could be either for timber or for fuel and fodder. Combining trees with grasses and legumes also helped to conserve soil and improve SOC. Seven years of continuous cropping (Gupta, 1995) under *Leucaena, Acacia nilotica,* and *Albizzia procera* resulted in 13 to 56% increase in soil organic carbon over the open grass (Control = 0.60). Forest differs widely in restoring organic carbon and improvement of alkali soils. Twenty years old plantations of *Prosopis juliflora, Acacia nilotica, Eucalyptus tereticornis, Albizzia lebbek* and *Terminalia arjuna* reduced the soil pH from 10.2 to 8.01, 9.03, 9.1, 8.67 and 8.67, respectively. Organic carbon content of the profile increased several fold over the original soil, the highest being under *Prosposis* and lowest under the *Eucalyptus* trees (Table 12).

Table 12 Effect of 20 years tree growth on the properties of an alkali soil

Tree species	Soil depth (cm)	pH	EC (ds m^{-1})	Organic C (%)
Acacia nilotica	0-15	8.4	0.25	0.85
	0-120	9.0	0.53	0.55
Eucalyptus tereticornis	0-15	8.5	0.44	0.66
	0-120	9.2	0.60	0.33
Prosopis juliflora	0-15	7.3	0.51	0.93
	0-120	8.0	0.41	0.58
Terminalia arjuna	0-15	7.9	0.32	0.86
	0-120	8.2	0.45	0.58
Albizzia lebbek	0-15	7.9	0.32	0.62
	0-120	8.7	0.51	0.47

Original soil properties; pH 10.2-10.5; EC 1.75-0.45 ds m^{-1}; OC 0. 12-0.24%

Source: Singh (1994)

The conversion of long-term arable crop land to agri-horticulture resulted in significant increase in SOC, soil biological activities, and fertilty status (Table 13). Under a system of different intercropped fruit trees, the cultivation of coconut (*Cocos nucifera* L.) inter-cropped with guava (*Psidium guajava* L.) enhanced the soil biological activities approximately 2-fold after 38 years over 10 yrs of the same intercropped system, and SOC increased from 3.4 to 7.8 and 2.4 to 6.2 g kg^{-1} after 38 and 10 years, respectively. The increase was attributed to greater recycling of bio-litters.

Table 13 Soil microbial activities of enzymes and carbon turnover rate in soils of different cropping systems at two sites in India

Field crop	SMBC (kg ha^{-1})	Soil respiration (mg CO_2-C kg^{-1} 10 d^{-1}	Dehydro-genase (µg TPF g^{-1} 24 h^{-1})	Phosphase (µg p-nitro phenol g^{-1} h^{-1})	SOC (t^{-1} ha^{-1})	C inputs (t ha^{-1} yr^{-1})	Turnover of soil organic C (yr^{-1})	C inputs/ SMBC ratio
Site A								
1. Coconut	50.42	110.2	79.2	101.3	9.0	0.98	9.2	1.94
2. Coconut + Sapota	1,384	116.0	109.1	123.0	18.9	2.82	6.7	2.04
3. Vegetable	1,340	116.1	127.3	143.1	21.0	2.44	8.6	1.82
4. Coconut + Guava	1,404	130.2	113.2	133.4	19.6	2.06	9.5	1.46
SEM±	5.01	11.8	4.2	3.0	0.59	0.05	0.20	0.01
LSD (P = 0.05)	12.31	NS	8.7	6.3	1.44	0.11	0.47	0.25
Original levels (1960)	268.3	90.1	46.1	81.2	6.8	—	—	—
Site B								
5. Coconut	442.3	48.2	36.2	43.2	6.4	0.96	6.6	2.2
6. Coconut + Guava	662.2	73.1	64.3	58.3	13.9	2.52	5.5	3.8
7. Coconut + Banana	975.1	94.3	48.0	86.4	15.4	2.30	6.7	2.4
8. Coconut + Custard apple	649.3	63.3	45.3	63.3	12.6	1.80	6.9	2.8
9. Coconut + Sapota	1,154	101.3	67.4	103.1	16.7	3.00	5.6	2.5
10. Coconut + Litchi	1,164	106.4	79.3	113.2	16.1	3.20	5.0	2.7
SEM±	8.6	5.6	2.1	3.1	0.33	0.15	0.11	0.07
LDS (P = 0.05)	18.1	11.3	4.3	6.5	0.73	0.33	0.22	
Original levels (1987)	210.3	40.3	22.4	33.1	4.8	—	—	

SMBC = Soil microbial biomass carbon, NS = not significant. (Source: Manna and Singh, 2001)

For sustainability of intensive cropping systems, it is not desirable to grow a particular crop or a group of crops on the same soil for a long period. As a corollary, productivity of soil can be prolonged if crops are changed over seasons or years. This principle led to the concept of cropping systems and is known and practiced since Vedic times in India and since the pre-Christian era in the west. Why modern agriculture has ignored it, is an enigma. The largest area in India is under rice and is grown in wet as well as dry seasons. Under intensive cultivation, two or three crops are grown per year. Most of the cropping systems are under cereal-cereal (rice-rice), cereal- cereal- cereal (rice-wheat-maize) and cereal-cereal-legume (maize-wheat-green gram) or finger millet (*Eleusine coracana Gaertn*)-wheat-gram (*Cicer arietinum* L.) or pearl millet wheat-green gram. The first, second and third crops are produced during the wet seasons (July-October), winter season (November-April), and summer season (May-June), respectively. Adoption of these intensive cropping systems depends on irrigation facilities, climatic conditions and introduction of high yielding cultivars and their management.

Crop sequence in Indo-Gangetic plains (rice-wheat) should be explored by introducing legume crops in the system in different ways, *viz*., replacing rice or wheat crop by a legume crop, i.e., rice by pigeon pea (*Cajanus cajan* L.) in summer or wheat by lentil in winter, or introducing a summer green manure crop like dhaincha (*Sesbania aculeata*) after the harvest of wheat and before planting of rice. The treatments having legume component have positive change. Mixed or intercropping systems are also advantageous in many ways when cereals or millets are mixed or intercropped with legumes. In a typical black soil (Vertisols) continuous cropping and mauring increased organic carbon content by 20 to 40% over a period of three years.

Strategies to enhance SOC

Strategies for enhancing the productivity of rain-fed crops and cropping systems and storage of SOC on sustainable basis are as follows:

1. Correction of limiting nutrient (s) including micronutrients and site-specific nutrient management approach in rainfed areas can help in augmenting the productivity.
2. Inclusion of short duration legumes in cropping systems.
3. Green leaf manuring with the help of nitrogen fixing trees like Gliricidia and Leucaena and off-season biomass generation and its incorporation.
4. Recycling and enhancing the quality of organic residues using effective composting methods.
5. Capitalization of the potential of microbes/bio-fertilizers.
6. Linking agricultural practices with short and long-term climatic forecast.
7. Adoption of site-specific soil and water conservation measures.
8. Appropriate crops and cropping systems for wider climatic and edaphic variability.
9. Enhancing the input use efficiency using the principle of precision agriculture.
10. Diversified farming systems for enhanced income and risk mitigation.
11. Ensuring credit, market access and crop insurance.
12. Controlling top soil erosion.
13. Conservation tillage (specially reduced and zero tillage) and surface residue management, mulching etc.
14. Balanced and adequate fertilization and integrated nutrient use.
15. Carbon sequestration through agroforestry tree species and its recycling by leaf litter fall.
16. Use of soil amendments.
17. Regular use of manures.

Summary

Continuous use of the same crop in the cropping systems, imbalanced and inappropriate use of chemical fertilizers and minimum or no use of organic matter year after year are the major constraints for restoring organic carbon in soil. The maintenance of soil organic matter in agricultural soils, particularly in semi-arid and sub-tropical regions of India is governed by annual temperature, precipitation and many interacting factors such as soil types, tillage, application of fertilizers, quality and quantity of organics returned to soil and the method of residue management. Soil organic carbon (SOC) usually decline when intensive tillage practices are followed which stimulate microbial decomposition of organic litter. However, reduced tillage practices can minimize SOC and loss. Increasing efforts are being made to enhance the level of organic carbon in soil by using different quality of organic matters *viz*., farmyard manure, crop residues, compost etc.; but these have proved insufficient as removal through plant biomass is much faster than feedback to the soil. High biomass productivity from soils of high SOC pool is attributed to better soil aggregation. Land use and soil management systems, which enhance the amount of biomass returned to the soil, also accentuates the terrestrial C pool. Different technological options include afforestation, and restoration of degraded ecosystem, establishment of bio-energy plantations with a large potential for biomass production, establishing perennials with a deep and prolific root system, growing species containing high cellulose are appropriate land use management options for better SOC storage in soil. Cultivation of fast growing trees with arable crops under agro-horticulture or agri-silviculture systems help in improving soil organic carbon. Alternate land use systems *viz*., agro-forestry, agri-horticultural, agri-pastoral and agri-silvipasture are more effective for soil organic matter restoration as compared to sole cropping systems.

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Soil Carbon Management in Hill Agriculture: Options and Opportunities in Northeast India

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Introduction

Soil organic matter (SOM) is primarily plant/animal residues in different stages of decomposition. The accumulation of SOM within the soil is a balance between the return or addition of plant animal residues and their subsequent losses due to decay by micro-organisms. SOM is important because it improves both the physical and chemical properties of soil and has several beneficial effects on soil quality. SOM helps to stabilize soil particles, thus decrease erosion. It also improves soil structure and workability; enhances aeration and water penetration, and increases water-holding capacity, and stores and supplies nutrients for growth of both plants and soil micro-organisms. Climatic conditions, such as temperature and rainfall, exert a major influence on the amount of organic matter in soil. Typically, accumulation of organic matter in soil is greater where there is more precipitation and cooler temperature. Decomposition of organic matter is greater in warmer and drier climates. Other factors that affect the rate of organic matter decomposition include soil aeration, pH level, and the microbial population in soils. Agricultural management practices can also influence the amount of SOM. Increased tillage of the soil decreases organic matter. Tillage increases aeration, which leads to drier soils and greater rates of decomposition. Increased summer fallow in crop rotation also decreases SOM, because fewer plant tissue residues are being added to the soils.Fertilization increases SOM because it increases biomass (above and below grounds production) and therefore, increases productivity. Increased use of manure and other soil amendments has similar effects. Increased use of forages in crop rotation increases SOM as forages deposit more residues than other crops. Irrigation has similar effects on SOM due to higher productivity and greater soil moisture.

Effects of warming on SOM dynamics remain a widely debated topic (Pendall *et al*., 2004). Intergovernmental Panel on Climate Change report (IPCC, 2007) predicts the global average temperature to increase by 1.1–6.4^0 C during the current century. Global warming is expected to profoundly impact ecosystem processes such as soil organic matter (SOM) dynamics (Von Fischer *et al*., 2008). Carbon (C) in SOM accounts for 80% of terrestrial C pool and is regarded as an important potential C sink that may help offsetting the greenhouse effect (Lal, 2008; Maia *et al*., 2010). Small changes in SOM stock under global change can potentially effect atmospheric CO_2 concentrations (Batjes and Sombroek, 1997; Marin-Spiotta *et al*., 2009). In addition, warming-induced changes in SOM regulate the availability of nitrogen (N) for plant growth and ultimately influence the net primary productivity of terrestrial ecosystems. Hence, it is imperative to understand how global warming will affect SOM dynamics. Changes in vegetation types are thus expected to alter the quality and quantity of SOM (Cheng *et al*., 2006; Fissore *et al*., 2008). Recent climatic warming has already led to dramatic shifts in plant functional groups and this can affect the accumulation and decomposition patterns of SOM by altering the quantity and quality of plant material entering into soil (Day *et al*., 2008).

Hill agriculture in the Indian Himalayas is spread over 14 states in Western and Eastern regions and cover about 16 % of the geographical area and 4 % of the total population of the country. Physiographically, the Himalayan zone could be divided into 3 distinct subzones: high Himalayas (> 3000 m), middle Himalayas (900 -3000 m) and lower Himalayas (< 900 m). The Eastern Himalayan region lies between the latitudes 26^o 40' - 29^o 30' N and longitudes 88^o 5' – 97^o 5' E and covers a total area of 93988 km^2 comprising Arunachal Pradesh, Sikkim and Darjeeling hills of West Bengal with 83743, 7096 and 3149 km^2 of area, respectively. In the north, the *Himadri* marks the international boundary with Tibet, which corresponds with the internationally accepted, well-known McMohan Line in the north-east. The Singalila range separates the region from Nepal in the west, while the Burma ranges of the Assam valley mark the eastern and southern boundary of the region. The Kingdom of Bhutan located between the Tibetan plateau and Assam-Bengal plains of India, separates Sikkim and Darjeeling hills from Arunachal Pradesh. The eastern boundary of the kingdom is Arunachal Pradesh while it is separated from Sikkim Himalaya by the Chumbi valley in the west. Purvanchal Himalaya is the eastern extension of the concealed Peninsular Block of Shillong Plateau. This block merges in the Tertiary ranges of the Purvanchal Himalaya, which belongs to the Great Arakan consisting of tightly packed parallel ridges and valleys. The Purvanchal Himalaya lies between the latitudes 21^o 5' - 28^o 23' N and longitudes 91^o 13' - 97^o 25' E, covering a total area of 108229 km^2 comprising Assam Hills (15322 km^2), Manipur (22327 km^2), Meghalaya (22429 km^2), Mizoram (21081 km^2), Nagaland (16579 km^2), and Tripura (10491 km^2). The region is extended in NE-SW direction touching the Tirap district of Arunachal Pradesh in the north-east and Chitagong Hill Tracts of Bangladesh in the south-west while Assam valley is the northern boundary. The region lies at a strategic position in North-East India having international boundary both in the east and the west with Myanmar and Bangladesh, respectively.

The constraints of hill farming are manifolds and some of the notable are ones as below:

- Soil acidity is the greatest challenge in NEH farms.

- Undulating topography, small fragmented and scattered land holdings, with very limited use of inputs.
- Due to the slopes, soils are prone to erosion, which is aggravated by heavy rainfall, migratory grazing leading to soil degradation.
- The land is inaccessible, and infrastructure, communications and mobility are obstructed by different physical, climatic, biological and socioeconomic factors.
- Despite sufficient water resources, irrigation facilities are meager, and most agriculture depends solely on rainfall.
- Improved technology has largely remained confined to irrigated areas and commercial crops.
- Shortage of energy and labour, especially women and children, which constituted 75-80% of family labour, due to their engagement in other activities .
- Natural hazards like intense rains, hailstorms, floods, epidemic diseases, insects and erratic monsoon.

Indigenous carbon management practices in NER

Numbers of indigenous farming systems are being practiced in NER and production is maintained only through organic nutrition. There are *Zabo* systems practised in Phek district of Nagaland which have a combination of forest, agriculture, livestock and fisheries. Rice based farming systems of Apatani plateau occupying a stretch of 26 sq km area in Subansiri district of Arunachal Pradesh is inhabited by “Apatani” tribe, bamboo drip irrigation system of Jaintia and Khasi Hills of Meghalaya, agriculture with Alder in Nagaland, rice cultivation on terraces in Nagaland, Manipur and Sikkim, Taungya System which is a method of establishing forest species in temporary combination with field crops are some of the systems which have inbuilt mechanism of resource conservation. Homestead Agroforestry where farmers of Assam and Tripura grow number of tree species along with livestock, poultry and fish mainly for the purpose of meeting their own needs is also a low inut hut popular system.

Of the 142.6 million hectares of net cultivated area in India, 57 million hectares (40 per cent) is irrigated. The remaining 85.6 million hectare (60 per cent) is rainfed. Mechanised farming is in areas under assured irrigation. In rainfed areas where the tilling of the soil is through traditional means, the soil health is better preserved than that in area under assured irrigation. It is a common knowledge that farmers resort to excessive use of fertilizers where there is assured irrigation. The farmers in rainfed areas by and large use organic manure and traditional farming practices. The fertilizer based technology of the green revolution and the much promoted growth oriented strategy pursued in agriculture has so far proved to be inappropriate for several agricultural systems in the developing world. In many of these systems based on the ground realities of the agro-ecology, farmers opted to retain traditional practices and emphasized their objectives towards stability, resilience and long-term sustainability/high productivity. The centralized process which guides the agricultural growth strategy in India is now giving way to a more sustainable road-map to development backed by indigenous knowledge and participation through regional planning. The key to such a plan can be provided by the regional strengths and weaknesses and the emerging market potentials. Such a strategy can be drawn on the observed responses evinced by the concerned agro-ecosystems to the incentives and limitations imposed by the mainstream development process. More attention is deserved by the fragile systems that also have ecological interactions with other regions and have not been adequately heeded by the policy so far. The regionally differentiated approach can accompany an effort to bring down dependence on fossil fuel based and environmentally damaging chemicals. Such dependence would also face the impact of liberalization and globalization in times to come. With changes taking place in the domestic and international economies, agricultural strategy in India can have a re-look at the north-east hill economies, learn from their failure to respond to the green revolution and focus on an acceptable format for the development of the region.

An analysis of the food grain production indicates that production from the high input belt, *viz*., from the 37 % area, has almost reached a plateau. On the other hand, the rainfed areas of the country, particularly the hill and mountain ecosystem which occupies 30.8 million ha areas, falls under Complex, Diverse and Risk Prone (CDR) agriculture which depends on the recycling of within-farm resources and off-farm wastes. In other words, CDR agriculture aims at production sustainability through crop rotation, mixed farming and intercropping. As stated by Bujarbaruah (2004), NE region has got immense potentiality to promote organic agriculture as the region has 8.8 lakh ha of land under shifting cultivation where no inorganic input and tillage is used. The region has varied agro climatic zones where the production from tropical to temperate agri-horticultural crops, animals and fishes persists. Inaccessibility, fragility and marginality of the entire area is thought to put a barrier in promotion of organic agriculture in the region. The need of the hour is to identify a commodity which has the potential to harness both domestic and international market.

C-management through organic crop nutrition

There are various ways through which C-management in soils can be made and the various avenues of organic crop nutrition are by the addition of animal dung/farmyard manure, green manure/tree leaf manure, crop residues, oilcakes, compost/vermicompost, bio-gas slurry etc. The present fertilizer consumption of 17.4 Mt in India may be raised to around 30-35 Mt of NPK (Tiwari, 2008) from various sources to produce 300 Mt of food grain in order to feed 1.4 billion population by 2025.

Animal manure

Livestock is the source of animal manure and their population in India including NER is presented in Table 1. Cattle produce 10-15 kg fresh faeces, pig 2-4 kg, sheep/goat 380-450 g/day with 45-80 % moisture and poultry 225 g droppings with DM of 56 g/day. In NE India, pig has got the largest animal population comprising of nearly 23 % of total population in India, thus indicating its potentiality in supplying the required animal manure for organic agriculture.

Table 1 Livestock population ('000)

Source	North East	All India	Per cent in NE region
Cattle	11,538	1,97,708	5.84
Buffalo	915	88,832	1.03
Sheep	157	56,766	0.28
Goat	4,085	1,20,774	3.38
Pig	3,097	13,581	22.80
Poultry	32,282	3,46,693	9.31

The average nutrients in animal dung (Fig1) indicate that pig dung contains the highest phosphate (1.8 %) and potash (2.2 %). Animal urine may also be utilized as a source of nutrients for maintaining soil fertility but proper care has to be taken for its collection and subsequent use. Perusal of data (Fig 2) indicates that pig urine contains highest amount of NPK as compared to other sources.

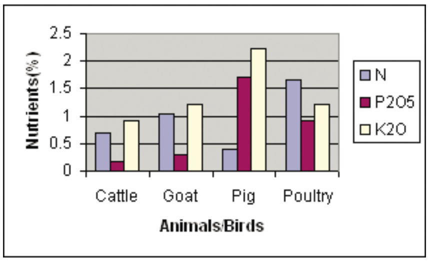

Fig1 Nutrients in animal dung

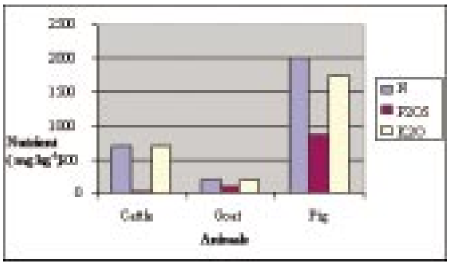

Fig 2 Nutrients in animal urine

Combining both the animal dung and urine components for supply of nutrients for crop production in NE India, it is projected (Table 2) that 61.5 % of the total potential nutrients, *viz*., 1.24 lakh tones could be available annually.

Table 2 Nutrient potential and actual availability ('000 t) from manure in NE region

Source	Commodity	Potential Nutrients (NPK)	Actually Available (NPK)
Cattle	Dung	130.90	91.63
	Urine	38.82	9.64
Goat	Dung	2.36	1.20
	Urine	0.28	1.25
Pig	Dung	1.48	0.74
	Urine	0.39	0.31
Poultry	Excreta	27.06	18.93
Total	-	201.29	123.70

The gross cropped area in NE India is 39.08 lakh ha.Considering the supply of nutrients from animal manure, only 15.4 kg N, 8.4 kg phosphate and 7.6 kg potash per ha could be supplied for crop production (Fig 3). It may be pertinent to mention that the cattle manure in India is estimated to be around 2 billion tones from which 3.44 Mt nitrogen, 1.3 Mt phosphate and 2.11 Mt potash could be available.

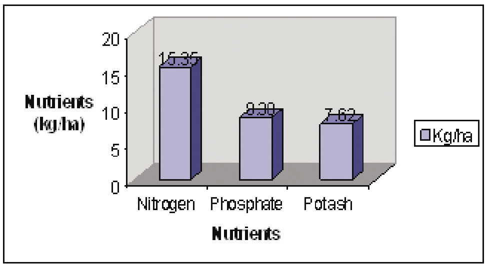

Fig 3 Nutrient supply from manure to gross cropped area (39.08 lakh ha) in NE region

Besides major nutrients available from animal manure in NE India, the supply of micronutrients could be sufficient to meet the demand of the crops grown in the region (Table 3).

Table 3 Supply of micronutrients (tonnes) to soils from manure in NE India

Manure	Zn	Mn	Cu	B
Cattle	376.2	1650.4	16.3	13.7
Goat/Sheep	403.4	23.7	9.6	726.1
Pig/birds	16.7	23.4	3.0	2.0
Total	796.3	1697.5	28.9	741.8
Supply to gross cropped area (g/ha)	204	434	7	190
Micronutrient removal (g/ha)	180	385	24	140

Tree leaf manure

Green leaf manure can also be an additional source of plant nutrients. Tree leaf supplied from hedge plantation could be used as manure and the contents of N, P and K varied from 2.42 to 3.20%, 0.32 to 0.62 % and 1.52 to 2.80 %, respectively (Table 4). It is noted (Table 5) that continuous application of green leaf from *Tephrosia* could raise 24 % sesamum productivity over fertilizer.

Table 4 Nutrient contents of leaves of different tree species

Tree leaf	N (%)	P (%)	K (%)
Leucaena leucocephala	3.20	0.58	1.92
Gliricidia maculata	2.90	0.50	2.80
Crotolaria tetragona	2.42	0.32	1.52
Tephrosia candida	2.74	0.62	1.58

Table 5 Productivity of sesamum (t ha^{-1}) after tree leaf application

Treatment	*Leucaena leucocephala*	*Tephrosia candida*	*Gliricidia sepium*
Fertilizer without leaf	1.18	1.19	1.32
Green leaf (10 t ha^{-1})	0.98	1.48	1.20

Buildup of soil organic matter could be possible through incorporation of forest litter as noted from a period from 4 to 16 years in Tripura (Fig 4).

Crop Residues

Crop residues (Fig 5) could also be a viable source for maintaining the soil health though the nutritive value of crop residues is less than the tree leaf. About 0.46 lakh tones of nutrients (Table 6) can be supplied from crop residues in NE India.

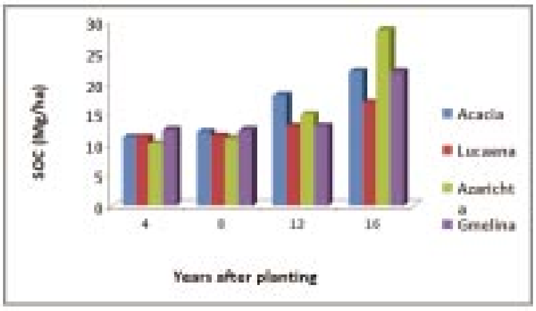

Fig 4 Forest litter to augment soil organic carbon

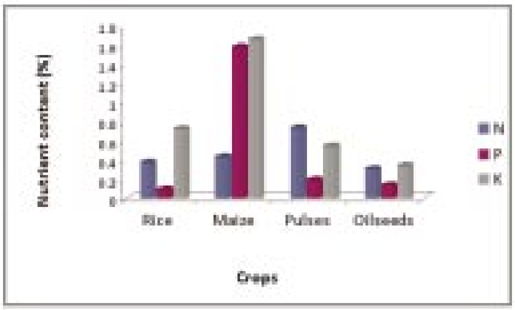

Fig 5 Nutrients from Crop residues

Table 6 Production (10^{6} t) and nutrient supply ('000 t) from crop residues in NE Region

Crop residues	Total production	Available production*	Potential nutrients (NPK)	Actual available nutrients (NPK)**
Rice	8.0	4.0	43.12	25.87
Maize	0.35	0.18	33.28	19.98
Pulses	0.17	0.09	1.29	0.29
Oilseeds	0.33	0.17	1.39	0.84

*50% of total produce, **40 % loss of total potential nutrients

Compost

The compost/vermicompost may be utilized for practicing organic agriculture in NE India as the C/N ratio of the materials may vary from 3.84 to 4.08. There are 3 types of earthworm, namely *Perionyx excavatas, Eudrillus eugeniae, Eisena foetida* which are generally used to make vermicompost from waste materials.

Table 7 Nutrient contents in compost

Organic amendments	Organic matter (%)	N (%)	P (%)	K (%)	Ca (%)	C:N
Compost	10.75	1.53	0.26	0.46	0.75	4.08
Vermicompost	12.42	1.88	0.20	0.38	0.64	3.84

A substantial rise (25 to 60 % over control) in the productivity of upland rice in Tripura was noted by the application of vermicompost (Fig 6).

Shifting cultivation and soil carbon

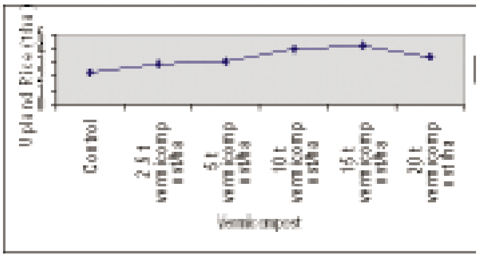

Fig 6 Effect of vermicompost on the productivity of upland rice

The shifting cultivation has caused the destruction of forest and species habitat, which accounts for the most profound losses in biodiversity. During the recovery phase (abandoned periods), the vegetation evolves towards the original climax condition. If full recovery is achieved before the area is again cultivated, the system can be sustainable. Ramakrishnan and Toky (1981) studied the dynamics of vegetation of abandoned *jhum* field. During the first 5 years, species diversity remained low and plots were dominated by herbaceous species. Between 5 and 15 years of abandonment, diversity increased rapidly as the vegetation passed into bamboo (*Dendrocalamus hamiltonii*)-dominated forest. Then it gradually passed into a mixed broad-leaved forest approaching the climax type. However, they could not follow the process beyond 20 years. Soil humic acid (Table 9) extracted from surface soils under shifting cycle was analysed for its characterization**.**

The ratio of optical densities at 465 and 665 nm (E_4/E_6) of humic acid showed a concomitant rise from 3.88 to 4.66 over the shifting cycle of 3 years. A high ratio of E_4/E_6 reflects a low degree of aromatic condensation and large proportion of aliphatic structures. So humic material with high E_4/E_6 ratio may be considered to have low aromatic condensation after 2nd and 3rd year of shifting cultivation. Like E_4/E_6 ratio, the CEC of humic acids also increased from 250 to 375 c mol (p^+) kg^{-1}. Both the reduced viscosity and molecular weight increased slightly in the 2nd year and then sharply declined from 10.85 to 8.05 mL g^{-1} and

6805 to 4300, respectively. This indicated smaller molecules of low molecular weight and low viscosity in soils under 3rd year of shifting cycle. Infrared studies showed the predominance of polymeric hydroxyl, carboxylic, carbonyl or quinone groups in humic acids with the rise in shifting cycle.

Table 9 Properties of humic acid in surface soils over the shifting cycle

Shifting cycle	E_4/E_6	CEC [cmol(p$^+$)kg^{-1}]	N_{sp}/C (mL g^{-1})	Molecular weight	IR spectral bands (cm^{-1})
1st year	3.88	250	10.55	6520	3915 (M), 3700 (W), 3580 (M), 2340 (Sh), 1873 (Sh) 1800 (S), 1600 (Sh), 1461 (Sh), 1039 (S), 913 (M), 690 (M), 535 (M), 470 (Sh), 425 (Sh), 348 (Sh), 261 (Sh)
2nd year	4.24	370	10.85	6805	3700 (M), 3624 (S), 2940 (Sh), 1610 (S), 1034 (S), 915 (S), 750 (M), 688 (S), 535 (S), 469 (Sh), 420 (W), 345 (Sh)
3rd year	4.66	375	8.05	4300	3700 (M), 3620 (S), 2000 (M), 1860 (Sh), 1845 (M), 1830 (Sh), 1640 (S), 1558 (Sh), 1030 (Sh), 1000 (S), 910 (M), 790 (W), 750 (Sh), 690 (M), 525 (M), 460 (M), 420 (Sh), 340 (Sh)

S = Strong, M = Medium, W = Weak, Sh = Shoulder.

Soil C under agroforestry systems

Status of soil humic acid under agroforestry systems was investigated. Dilute alkali solouble humus as well as humin fractions were also estimated and the data are presented in Table 10. The amount of humin organic carbon content was maximum (5.35 g kg^{-1}) in soils under *Acacia auriculiformis,* followed by *Gmelina arborea* (4.47g kg^{-1}). Soils under *Azadirachta indica,* though showed a high value of organic carbon, contained low humin carbon (2.13 g kg^{-1}). This low humin carbon in soils under *Azadirachta indica* showed only 7.6 per cent of organic matter humification. On the other hand, dilute alkali soluble humic carbon underwent a variation from 7.4 g kg^{-1} to 26.5 g kg^{-1}. This indicated accumulation of alkali soluble humus in high amount in soils under *Azadirachta indica* (26.5 g kg^{-1}) followed by *Gmelina arborea* (17.3 g kg^{-1}), *Michelia champaca* (15.9 g kg^{-1}), *Eucalyptus hybrid* (15.1 g kg^{-1}). This showed an increase in humus accumulation in soils under MPTs compared to open space (7.4 g kg^{-1}). The ratio of alkali soluble organic carbon and humin organic carbon (*R*) showed a variation from 3.1 to 13.2. The lower the value of the ratio, the higher would be the humification rate. So soils under *Acacia auriculiformis,* showing the least value of the ratio (3.1) indicated the high humification rate. On the other hand, lower the value of inverse ratio, the lower would be the rate of humification and *vice-versa*. Comparatively, high value of inverse ratio in soils under *Acacia auriculiformis*, *Leucaena* *leucocephala* and *Gmelina arborea* indicated high humification rate. E_4/E_6 ratio of the absorbance of humic acid solution at 465 nm and 665 nm is also an index of humification. The low value of E_4/E_6 ratio indicated a high degree of humification of soil humic substances and high value indicated low degree of humification. Here, E_4/E_6 ratio was found to vary from 1.64 to 5.38, thus showing low degree of humification in soils of open space (E_4/E_6 ratio 5.38). On the basis of E_4/E_6 ratio, it can be said that soils under the canopy of *Acacia auriculiformis, Michelia champaca*, *Tectona grandis* and *Dalbergia sissoo* showed low humification of the organic matter. But soils under the canopy of other MPTs showed high humification due to low value of E_4/E_6 ratio of soil humic substance. Soils of open space had low humification due to high E_4/E_6 ratio. All other soils under MPTs indicated humification higher than soils of open space.

Table 10 Humus[a] in soils under MPTs

MPTs	Humin O. carbon ($g\,kg^{-1}$)	Alkali soluble O.carbon ($g\,kg^{-1}$)	Humin O. carbon (%)	Ratio of alkali soluble & Humin O. carbon (*R*)	E_4/E_6 ratio
Acacia auriculiformis	5.35	16.60	24.40	3.10	4.47
Morus alba	2.25	13.70	14.20	6.10	3.15
Leucaena leucocephala	2.58	14.10	15.40	5.50	3.56
Dalbergia sissoo	1.21	12.70	8.70	10.50	4.73
Gliricidia maculata	1.14	13.80	7.70	12.10	1.91
Azadirachta indica	2.13	26.50	7.60	12.40	2.37
Michelia champaca	1.05	15.90	6.20	15.10	5.01
Eucalyptus hybrid	1.04	15.10	6.50	14.50	1.64
Tectona grandis	1.13	11.80	8.80	10.40	4.00
Gmelia arborea	4.47	17.30	20.50	3.90	3.35
Samania saman	1.04	12.90	7.50	12.40	1.83
Albizia procera	1.04	13.70	7.10	13.20	2.30
Open space	1.75	7.40	24.70	4.20	5.38
Mean	2.05	14.70	12.30	9.50	3.70
CV (%)	14.3	28.20	53.80	43.60	36.80
LSD (P=0.05)	0.21	2.54	0.51	1.14	0.26

Note: [a] Average values from 4-16 years

Carbon sequestration

Carbon sequestration refers to the capture and long-term storage of carbon in forests, soils or in the water body, so that the build-up of carbon dioxide (one of the principal greenhouse gases) in the atmosphere will reduce or slow. Managing land and vegetation to increase carbon storage can buy valuable time to address the ultimate challenge of reducing greenhouse gas emissions. Article 3 of the Kyoto Protocol allows for the offset of emissions by investing in activities that increase carbon sequestration. This would generally involve an investor or buyer being issued with "carbon credits" corresponding to the amount of carbon sequestered by these activities. These credits could then be used to offset part of the buyer's net greenhouse gas emissions (for example from their electricity or steel manufacturing plant). This provides a relatively low-cost opportunity for the private sector to reduce emissions while promoting a comprehensive and environmentally responsible approach to climate change. There are three main types of carbon sequestration:

- Carbon sequestration in terrestrial ecosystems - Increasing the amount of carbon stored in vegetation and soils;
- Carbon Sequestration in the water body - Enhancing the net uptake of carbon from the atmosphere by the oceans, through fertilisation of phytoplankton with nutrients and injecting carbon dioxide to ocean depths greater than 1000 meters; and
- The subsurface sequestration of carbon dioxide in underground geological repositories.

All of these options are commonly known as carbon "sinks". The first, increasing carbon storage in terrestrial ecosystems, is currently the focus of the most attention and is the easiest and the most immediate option at present. The other options may become more important in the future, as the science and legal systems develop. Plant growth occurs through the process of photosynthesis, during which carbon is captured and stored in plant cells as the plant grows. Over time, branches, leaves and other materials fall on the ground, gradually losing their stored carbon back to the atmosphere as they decompose. A portion of the carbon from this decomposing plant litter may sometimes be captured by organisms living in the soil, or through processes involving plants' root systems. The terrestrial ecosystem currently sequesters carbon at a rate of about two gigatonnes each year (2 Gt C $year^{-1}$). With careful management, this could be significantly increased by several gigatonnes per year, providing a critical period of "bridging technology" while other carbon management options are developed. Carbon sinks in this category may be living, aboveground biomass (trees) products with a long, useful life created from biomass (timber), living biomass in soils (roots and microorganisms), or organic and inorganic carbon stored in soils and deeper subsurface environments.

Conclusion

In the NE region where the fruits of green revolution are yet to be harvested, intensification in agriculture would involve a complete package of practices centred around increased supply of plant nutrients. Organic carbon content of the soils in the entire NE India is high, except some parts of Assam and Tripura. The total forest cover in the region is 1,41,652 sq km, which is about 54.1% of the geographic area as against the national average of 19.39%. However, there is drastic reduction in dense forest cover (canopy density > 40%) in most of the states *viz*., Manipur and Meghalaya have dense forest cover of 25.57 and 25.33 %, respectively. Similarly for Nagalnd, Sikkim, Tripura and Mizoram, the dense forest cover is 32.53, 33.70, 33.02 and 42.39%, respectively. Among seven sisters of NEH, Arunachal Pradesh is the only state, which has the dense forest cover of 64.0%.

Historically, soils have lost 40-90 Pg carbon (C) globally through cultivation and disturbance at a rate of about 1.6 0.8 Pg C y^{-1}, mainly in the tropics. Since soils contain more than twice the C found in the atmosphere, loss of C from soils can have a significant effect on atmospheric CO_2 concentration, and thereby on climate. Halting land-use conversion would be an effective mechanism to reduce soil C losses, but with a growing population and changing dietary preferences in the developing world, more land is likely to be required for agriculture. Maximizing the productivity of existing agricultural land and applying best management practices to that land would slow the loss of soil C. There are, however, many barriers to implementing best management practices, the most significant of which in developing countries are driven by poverty. Management practices that also improve food security and profitability are most likely to be adopted. Soil C management needs to be considered within a broader framework of sustainable development. Policies to encourage fair trade, reduced subsidies for agriculture in developed countries and less interest on loans and foreign debt would encourage sustainable development, which in turn would encourage the adoption of successful soil C management in developing countries. If soil management is to be used to help addressing the problem of global warming, priority needs to be given to implementing such policies.

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Role of Soil Erosion and Deposition in Stabilization and Destabilization of Soil Organic Carbon

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Introduction

Soil erosion and sediment transport, and deposition represent a serious problem throughout the world, because of their impact on sustainable agricultural production as well as on environmental conservation. Severe erosion may promote land degradation, especially in semiarid and humid subtropical environments that are common in India. Soil is an important element of the global carbon (C) cycle. Soil erosion from agricultural land results in considerable losses of soil organic matter (SOM). Considering that approximately 1.6 billion ha or 13% of the earth surface is affected by human-induced erosion (GLASOD, 1990), and current annual soil loss in India is as high as 6.6 billion Mg per year (Wen and Pimentel, 1998), erosion-induced C displacement may be an important factor affecting CO_2 concentration in the atmosphere (Lal, 1995). Soil erosion is a four-stage process involving detachment, breakdown, transport/redistribution and deposition of sediments. All these processes have strong impact on SOM. The clay and soil organic carbon (SOC) are influenced during all the four stages. Being a selective process, erosion preferentially removes the lighter fractions. A combination of mineralization and C export by erosion causes severe depletion of the SOC pool on eroded soils compared with uneroded or slightly eroded soils. In addition, the SOC redistributed over the landscape or deposited in depressional sites may be prone to mineralization because of breakdown of aggregates leading to exposure of hitherto encapsulated C to microbial processes. Depending on the delivery ratio or the fraction of the sediment delivered to the river system, gross erosion by water may be 75 billion Mg, of which 15–20 billion Mg are transported by the rivers into the aquatic ecosystems and eventually into the ocean. The amount of total C displaced by erosion on the earth, assuming a delivery ratio of 10% and SOC content of 2–3%, may be 4.0–6.0 Pg $year^{-1}$ (Lal, 2003). With 20% emission due to mineralization of the displaced C, erosion induced emission may be 0.8–1.2 Pg C $year^{-1}$ on the earth. Thus, soil erosion has a strong impact on the global C cycle and this component must be considered while assessing the global C budget. Adoption of conservation-effective measures may reduce the risks of C emission and sequester C in soil.

The overall impact of human-induced erosion on the global C cycle is not very clear. Assessment of this impact is likely to depend on the scale at which erosion is considered (van Noordwijk *et al.,* 1997). For example, on the field or watershed scale, it is generally recognized that loss of soil results in reduction of SOM concentration (Gregorich *et al.,* 1998; Lal, 2003). However, when deposits such as colluvium, alluvium, aeolian as well as reservoir and lake sediment masses are considered, it is plausible that the erosion-induced burial of C is substantial, perhaps as high as 0.6–1.5 Pg year^{-1} (Stallard, 1998). Although the question of the SOM fate during transition from sediment sources to sediment sinks has been raised in the literature (Lal, 1995) and some generalizations have been made (Jacinthe and Lal, 2001). Field data are scarce, investigations are limited to few pioneering studies (Bajracharya *et al.,* 2000; Jacinthe *et al.,* 2002), and the magnitude of CO_2 release to the atmosphere from the sediment during transport phase is largely unknown (Jacinthe *et al.,* 2001).

The possibility of erosion-induced C sequestration has received widespread interest from the scientific community and policymakers for three reasons. First, erosion is among the most pressing environmental problems facing the world today. Accelerated erosion by water and wind is responsible for one-half and one-quarter of all soil degradation, respectively (Daily, 1995; Pimentel *et al.,* 1995). Persistently high rates of soil erosion affect more than 1.1×10^9 hectares of land annually (Jacinthe and Lal, 2001; Berc *et al.,* 2003), redistributing on the order of 75 Pg soil per year, with sediment transport leading to silting of reservoirs and eutrophication of lakes. Soil erosion from agricultural lands alone, which accounts for two-thirds of the total soil loss, has been estimated to worth more than US$400 billion of damages annually (Pimentel *et al.,* 1995). Second, projected changes in climate are expected to stimulate the hydrologic cycle, increasing the intensity, amount, and seasonality of precipitation in many parts of the world, and thus accelerating soil erosion (Berc *et al.,* 2003). Third, soil erosion is the only way by which stable, mineral-associated SOC can be relocated in large quantities and its decomposition rate is enhanced during transport and reduced after transport (Starr *et al.,* 2000, Lyons *et al.,* 2002).

Assessment of erosion-induced C losses are usually based on comparative observations between disturbed (either loss or accumulation) and undisturbed sites (Harden *et al.,* 1999). Due to a large number of soil types, climatic and topographical conditions at the given sites and often lack of detailed site description, these relationships are difficult to generalize and extrapolate beyond the studied domain. To overcome the limitation of field observation studies, modeling of SOM loss due to water and wind erosion may be a viable option (Starr *et al.,* 2000). Assessment and prediction of erosion-induced release of CO_2 into the atmosphere requires integration of field results obtained at various scales and at different climatic and soil conditions with current C dynamics and soil erosion models.

Factors affecting erosion-induced soil organic matter turnover

Wide variety of views on the role of erosion on C dynamics within ecosystems indicate that the processes involved in detachment, transport, deposition and mineralization of SOM are poorly understood. Discrepancies in estimates of erosion influence on soil C may point out to differences in SOM quality at various landscape positions (Schimel *et al.,* 1985a) resulting from SOM transport and sorting by water. The SOM trapped in the watershed deposits can be either sequestered or undergo increased rate of mineralization depending on local conditions. Soil erosion affects SOC dynamics through its impact on the following processes: (i) slaking or disruption of aggregates, (ii) preferential removal of C in runoff water or dust storms, (iii) mineralization of soil organic matter on-site, (iv) mineralization of SOC displaced and redistribution over the landscape and transported in rivers and dust storms, (v) reaggregation of soil through formation of organo-mineral complexes at the depositional/ protected sites and (vi) deep burial of C-enriched sediments in depositional sites, flood plains and reservoirs and ocean floor (Fig. 1).

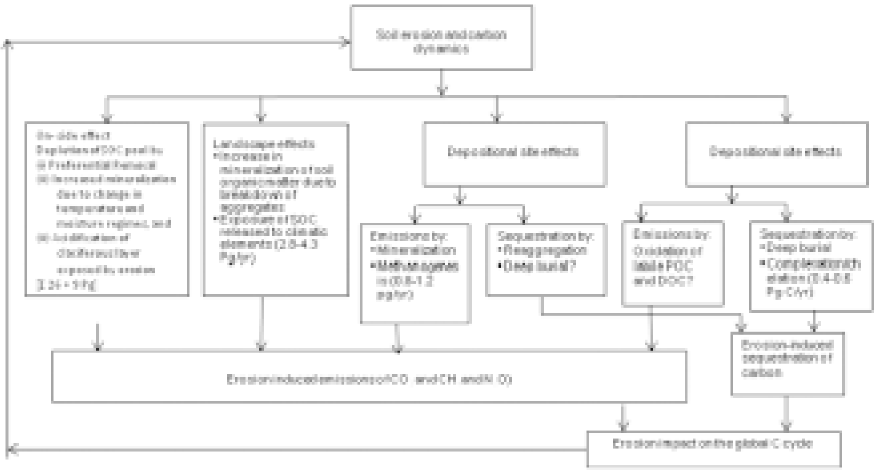

Fig 1 Erosion impact on processes that impact the global C- cycle

Types of soil organic matter and its distribution in soil matrix

Accelerated soil erosion has significant influence on the global C budget (Blaikie and Brookfield, 1987). The net amount of CO_2 released from the biosphere to the atmosphere as a result of land use change over time is likely to be equivalent to about 75% of total fossil fuel C emissions. It is estimated that since the Industrial Revolution, land conversion and degradation have caused up to 200 Pg C release to the atmosphere that was originally in the biosphere (DeFries *et al.,* 1999).The SOM consists of a great variety of organic compounds. For modeling purposes, however, it is usually classified into three pools based on the rate of mineralization and turnover (Stevenson, 1982). Labile or easily mineralizable compounds along with microbial and fungal biomass generally comprise about 5–15% of the total SOM. This pool has turnover rate of month to years and, perhaps, is of greatest interest for SOM erosion modeling. Slow pool with turnover time of several decades comprises 20–40% of the total SOM. Stable pool has turnover time of hundreds to thousands of years and in most soils comprises remaining 60–70% of the total SOM (Rice, 2002).

Sediment enrichment

Runoff from eroding landscapes is enriched in clay sized particles (Pert and Walling, 1982), particulate organic carbon (POC), and dissolved organic carbon (DOC) (Lal, 1995). Majority of the suspended sediments in rivers will be less than 0.062 mm diameter (Pert and Walling, 1981). The smallest size SOC fraction (less than 0.005 mm) is thought to be the most stable size fraction in soil (Paul *et al.,* 1995) because of the physical protection afforded in soil aggregates (Kay, 1998) and the recalcitrance of humic materials (Paul *et al.,* 1995). Physical protection in aggregates is undermined by the processes such as tillage and water erosion (Lal, 1997). Erosion is one of the soil processes that can remove stable SOC in large quantities; so its effects may be dramatic. The data presented by Mitchell *et al.* (1998) on modeling carbon storage in soil showed that erosion by water is the most significant factor affecting the SOC balance in the north central USA.

Enrichment ratio of SOM is the ratio between concentrations of SOM in sediment to those in undisturbed soil. Enrichment ratio >1 is the result of preferential transport of either soil or SOM. Enrichment of eroded sediment with nutrients and SOM has been widely reported (Owens *et al.,* 2002). Its mechanism consists of two processes: dispersion of soil aggregates and their sorting during transport. Rain drop impact is one of the primary erosive forces acting on soil. It was shown that upon impact with soil aggregate, raindrop removes its outer layer (slaking and peeling process), thus releasing microaggregates. The mechanism of enrichment is explained by the fact that the outer layers of soil aggregates have increased concentration of sorbed chemicals including SOM compared with the inner core (Ghadiri and Rose, 1991a). Raindrop impact causes the aggregates to slake and peel. As a result of this process, eroded sediments not only have finer size characteristic than the original soil, but also SOM is unevenly distributed between coarse and fine particles (Palis *et al.,* 1997). These structural factors, although difficult to quantify, need to receive more attention when modeling erosion-induced SOM dynamics. The sorting of materials transported by water is caused by the differences in drag, gravitational, and cohesive forces acting on individual particles. The drag force is a function of the particle diameter and shape, and the gravity force is a function of particle mass. The enrichment ratio of SOM as high as 5 has been reported (Zobeck and Fryrear, 1986) for certain conditions. Although the amount of loose, poorly decomposed non-cohesive plant fragments in most agricultural soils is relatively small, its highly preferential transport may also have a significant impact on SOM redistribution (Ghadiri and Rose, 1991b). Enrichment ratio of SOM tends to be greater for more aggregated soils with higher concentration of clay than less aggregated and coarse-textured soils (Palis *et al.,* 1997). The SOM concentration in various sizes of aggregates tends to decrease with the severity of erosion (Bajracharya *et al.,* 2000). It also varies with rainfall duration. For example, in an experiment under various levels of erosion, enrichment ratio of SOC in a sandy loam soil varied from 1.45 to 2.65 (Fig 2) with severity of erosion (Mandal *et al.,* 2012).

Soil structural controls over decomposition of soil organic matter in disturbed soil

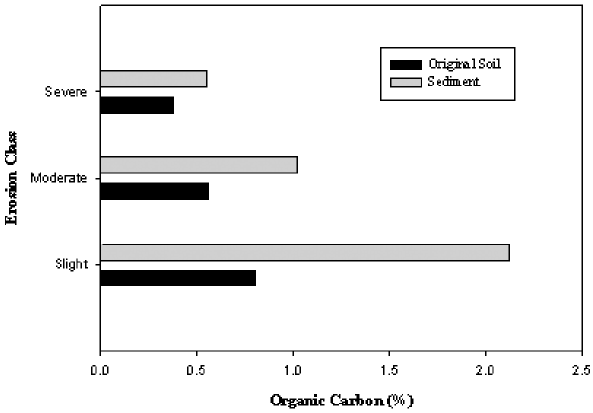

Fig 2 Concentration of organic C (%) in soil and sediment under different erosion levels

While the effect of soil moisture and temperature regimes as well as management practices on the rate of SOM dynamics has received some attention (Rickman *et al.,* 2002), soil structural controls over SOM decomposition have not been given proper attention. Aggregate structure is one of the soil properties most significantly affected by erosion. Soil detachment and sediment transport alter aggregate structure which to a great extent controls decomposition of organic substances by microorganisms (Vanveen and Kuikman, 1990). The slaking and peeling process, described earlier, is an important factor in decomposition because aggregate breakdown occurs along intra-aggregate pores, which are the preferable sites of sorption for SOM as well as other chemicals (Wan and El-Swaify, 1998). The amount of pores directly accessible to bacteria is estimated to be 5% (Vanveen and Kuikman, 1990), which suggests that much of substrate is physically protected from bacteria. Little data is available that quantifies how much of CO_2 evolution increase is attributed to the aggregate breakdown, although it is reasonable to hypothesize that this process occurs. Decomposition of SOM in liquid and soil phases was shown to have different rates (Vanveen and Paul, 1981), which suggests that soil architecture provides certain protection against decomposition.

Being a work function, erosion causes slaking, disruption and breakdown of aggregates. The latter may happen by slaking caused by a quick immersion in water, disruption following the escape of compressed or entrapped air, impact of the raindrop related to its kinetic energy or momentum, shearing force of runoff or wind, or collision of aggregates against one another. Whereas the process of aggregation sequesters C, breakdown or dispersion of aggregates into soil separates releases hitherto encapsulated C and makes it vulnerable to decomposition by microbial processes. In addition to exposure to microbial processes, the C thus released by slaking is also preferentially removed by water runoff or wind, redistributed over the landscape or is carried into depositional/protected sites.

Sediment transport and sediment yield

Studies, which investigated correlation of SOM with topographical position, reported increased concentration of SOM at footslope locations (Bergstrom *et al.,* 2001). Although increased SOM concentration may be partially attributed to greater SOM input due to local hydrological factors, the increase of C:N ratio in such locations (Schimel *et al.,* 1985a) might suggest different organic matter quality probably resulting from selective transport of organic matter. After rainfall event, most of displaced SOM remains within watershed. Large discrepancies were observed between the amount of soil displaced from the field and the amount of sediment delivered to the stream (Walling, 1983). The three ways of SOM loss associated with erosion are oxidation due to aggregate breakdown during detachment and transport of SOM (presumably more mobile and less dense and cohesive), transformation of SOM into more stable pool, and transfer of SOM into water bodies. Storage of sediment in digressional sites and fluvial plains can be substantial (Stallard, 1998; McCarty and Ritchie, 2002) thus allowing SOM from disrupted aggregates to be exposed to environmental factors for prolonged periods of time. Transport of sediment from watershed is a multistage process during which soil may be temporarily deposited on its way to the streams or permanent deposition sites. The CO_2 flux from the disturbed aggregates is proportional to the time these aggregates reside on the landscape before being buried or delivered to an aquatic system. In most studies in natural conditions, enrichment of SOM in sediment distributed within watershed is reported to be higher than unity (Ghadiri and Rose, 1991b), which may not necessarily be the case with sediment leaving watershed. A study of sediment delivery into 41 impoundments in continental US (Avnimelech and McHenry, 1984) demonstrated decreased concentration of SOM compared to the soils of their origin in cases when these soils had high SOM concentration. These two seemingly contradictory observations indicate that displaced SOM accumulates within watershed boundary and perhaps substantial portion of it mineralizes before reaching water bodies (Jacinthe and Lal, 2001). About 70% of the SOM from the colluvial source decomposed during translocation or after deposition on a sandy soil in Northwest Germany (Beyer *et al.,* 1993) where selective preservation of SOM in the colluvial sink was hypothesized. The erosion-induced losses of SOM into the atmosphere in the described cases are quite substantial considering the size of labile SOM pool reported in the literature for most of agricultural soils (Rice, 2002).

Modeling

Erosional redistribution of soil and associated soil organic carbon

Soil erosion is traditionally conceived as a three-step process involving the detachment, transport, and deposition of soil particles. Detachment exposes SOC that is physically protected within aggregates and clay domains. Subsequently finer soil particles and associated SOC are preferentially transported away from eroding slopes to different low-lying depositional sites (Gregorich *et al.,* 1998; Starr *et al.,* 2001). Following detachment and transport, burial usually is believed to protect SOC from decomposition, because there are generally enhanced and radiometrically old C stocks in the deep soils of agricultural lowlands and sedimentary basins (Stallard, 1998; Harden *et al.,* 2002). Most (>70%) of the eroded topsoil remains within the adjacent topography and is stored in a variety of depositional basins, including wetlands, peat lands, estuaries, fluvial deltas, terrestrial depressions (hollows), and reservoirs within the same or adjacent topography (Stallard, 1998). The increased wetness and reduced aeration at the depositional basins (compared with eroding slopes) can slow down decomposition (Stallard, 1998, Smith *et al.,* 2001; McCarty and Ritchie, 2002). Stallard (1998), on the basis of past data and model simulations, provided three major reasons why soil erosion should not necessarily represent loss of C from the terrestrial biosphere: First, soil redistribution downhill or downstream is usually accompanied by partial replacement of eroded upland C with new photosynthate. Second, a significant portion of the eroded C-rich topsoil is buried in different depositional settings, rather than flowing to the ocean. Erosion transports relatively fresh organic matter that is present at or near the soil surface (compared with deep soil organic matter. After successive erosive events, the C and nutrient-rich topsoil of the eroding slopes is buried in the depositional lowlands and becomes a subsoil horizon of the convergent slopes or plains (Fig 3), probably reducing its rate of decomposition (compared with noneroded C on the contributing slopes). Third, the surface area for terrestrial deposition of eroded C has increased since the beginning of the Industrial Revolution. The estimated 10- to 100-fold acceleration of erosion rates by anthropogenic activities in recent history has not been accompanied by a concurrent and proportional increase in sediment discharge to the ocean. The discharge of sediment and C to the ocean has remained approximately constant as a result of hydrologic projects on managed floodplains. Therefore, the recent increase in the

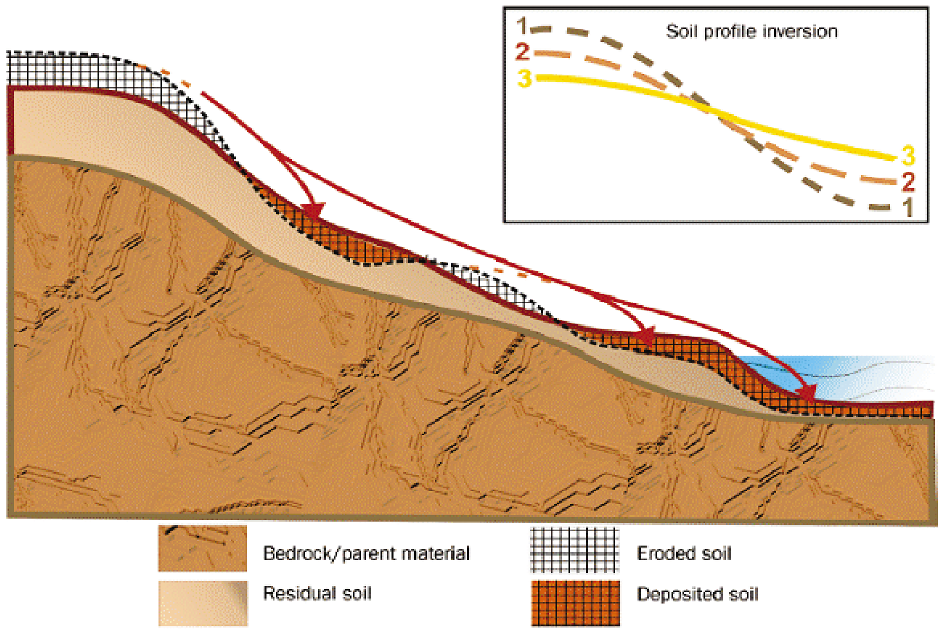

Fig 3 Soil and soil organic carbon transport from divergent slopes to convergent or flat depositional basins and erosion-facilitated inversion of a hillslope soil profile

rate of soil erosion has led to increased storage of eroded C in different types of depositional basins (Stallard, 1998).

General structure of soil organic matter models

Little is known of the properties and fate of SOC that is translocated from erosion to deposition points on the landscape. The physics of particle settling would tend to suggest that the extent of erosional translocation is negatively correlated with the size and density of detached soil aggregates and primary particles. Thus, soil erosion is a highly selective process that preferentially removes the smallest and lowest density components of soil and transports them great distances (Lal, 1995). It is important to develop diagnostic models that will improve our understanding of the underlying mechanisms and processes affecting erosion induced losses of SOC. Available data on erosion and deposition of SOC are very limited, so our approaches to diagnostic modeling are based on the information on the transport of soil and drawing inferences concerning the closely related transport of SOC.

The empirical model fits the observed data from individual events better than the linear parametric model. Because the empirical relationship is a power law, it is not as easy to draw broader inferences from the results as with the linear parametric model. For instance, calculation of cumulative C losses from data on cumulative soil losses is not trivial. The general logarithmic linearity seen in these data are essentially the same functional forms as the parametric model discussed above with a log-linear relation between enrichment ratio and soil loss is remarkably similar to what has been observed by previous researchers (Massey and Jackson, 1952). The proposed empirical relationship is of the form:

$$\text{SOC loss} = a\,(\text{soil loss})^{b} \quad \text{.......................................(1)}$$

Where a and b are statistical constants. This empirical formula does not require an explicit expression for ER, an advantage for watershed scales where source materials of different SOC contents contribute to a composite mixture in runoff. A study by Collins *et al.* (1997) showed the complexity of relating eroded sediment to source material in intermediate sized watersheds (10 km scale). In this study, ER ranged from 0.5 to greater than 5 depending on stream bank, forest, pasture, or cultivated soil source material. This empirical model only predicts C losses from these watersheds for events with given soil loss. The two watersheds however exhibit nearly identical equations and it would be an interesting course of future research to add more data to this graph from different areas and different scales in an effort to understand the underlying processes affecting the relationship between soil and SOC loss.

Each of the modeling strategies has associated advantages and disadvantages but these strengths and weaknesses generally complement one another. One disadvantage common to all these models is that they do not assess indirect effects such as reduction in SOC inputs because of crop productivity decline (Gregorich, *et al.,* 1998) and increased carbon dioxide losses of translocated SOC (Lal, 1995). Empirical models are helpful for understanding the relationships between soil and SOC losses in specific watersheds and statistical estimates of accuracy may be established once the models are calibrated. However, there is a need for long-term monitoring to obtain calibration data, the derived relationships only apply to specific watersheds, and this approach requires input data for specific runoff events. Simulation models play an increasingly important role in C pools assessment at different spatial scales as well as in understanding of processes underlying C fluxes in ecosystems (Izaurralde *et al.,* 1998). Models are also essential tools for devising and evaluating management practices intended to balance global C fluxes. The Soil Organic Matter Network (SOMNET) database (Molina and Smith, 1998) identified 33 SOM dynamics models available for use and the database is being continuously updated. A great variety of models designed for different spatial scales and time steps can be classified into four groups according to the conceptual approach to SOM turnover in soil: (i) process-based (single or multicompartment), (ii) cohort, (iii) food-web chain, and (iv) combined (Smith, 2002). Majority of the models are process-based multi-compartment models. The characteristic features of these models are: (i) subdivision of the SOM into several ‘‘homogeneous’’ pools, each with its unique decomposition rate, (ii) assumption that decomposition of SOM follows first-order kinetics, (iii) defined relationship between the dynamics of C and N pools (Paustian, 1994). Different C pools of different properties combined with flows of C between the pools represent the structure of process-based models. The output from a component of the SOM system may be split or have a back loop to account for the process of microbial succession (Molina and Smith, 1998). Modular structure of SOM models allows flexibility and ability to expand the model structure to accommodate new processes and flows as empirical data such as connection between microbial community and soil structure. Structural effects on decomposition rates and effect of water, wind and tillage on erosion becomes available. Each module occupies specific position in the C flow hierarchy, and is characterized by a decay rate. Most of SOM models do not explicitly specify C flows due to erosion, but allow inclusion these flows, if necessary. A general concept of SOM dynamics as affected by soil water erosion is presented in Fig 4.

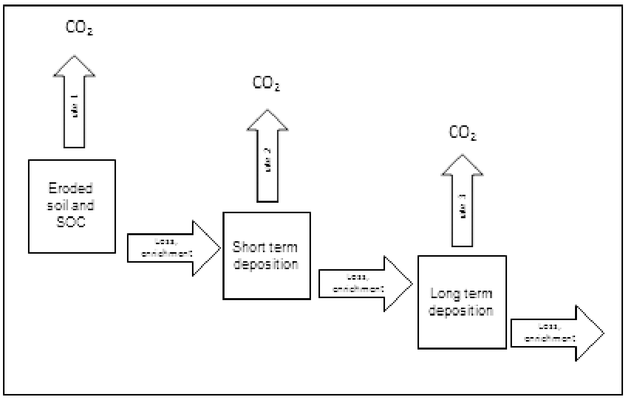

Fig 4 Soil organic matter fluxes as influenced by soil erosion

Principal governing equation of erosion component in soil organic matter models

Three major processes involved in erosion-induced SOM turnover can be defined as: (i) physical removal of SOM from slopes and convex landforms (ii) deposition of SOM in depressions and on concave landforms (iii) change in the rate of mineralization of displaced C. Loss of C by SOM models is usually estimated in relation to soil loss (Gregorich *et al.,* 1998). One of the most common approaches is a linear relationship (Starr *et al.,* 2000):

$C_{LOSS} = A \cdot C_{SOIL} \cdot Er$ ....(2)

where A= spatial average soil loss (Mg ha^{-1} $year^{-1}$);

C_{SOIL}= concentration of organic C in soil (%); Er = enrichment ratio of eroded sediment relative to the original soil (dimensionless).

Soil loss is included as a component in several SOM models such as Century or EPIC (Goss *et al.,* 2001). Century model employs the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), which depends on rainfall to determine erosive energy. The USLE uses six erosion factors to compute the average annual soil loss on field slope as:

A = RKLSCP ....(3)

where, R = rainfall erosivity factor, which includes runoff factor from snowmelt; K = soil erodibility factor, which is correlated with soil particle size distribution, OM content, permeability, etc.; L= slope length factor; S = slope steepness factor; C = cover and management factor, which describes the type of soil cultivation and the degree of soil protection by plant canopy; P = support practice factor related to the type of erosion protection practice such as terracing, stripcropping, etc.

Another erosion prediction tool, MUSLE, is used in EPIC model (Williams, 1975). The limitation of the described soil loss prediction equations is their inability to account for soil deposition. The SOM turnover process in depositional areas is a key component of C balance in terrestrial ecosystems (Bajracharya *et al.,* 2000). Although SOM mineralization in soil as affected by soil structure and degree of disturbance has been studied (Vanveen and Kuikman, 1990; Parton *et al.,* 1993), attempts to incorporate the contribution of displaced sediment into CO_2 flux were limited (Harden *et al.,* 1999; West and Wali, 2002).

The principal governing equation of C flux between SOM model components is firstorder relationship:

$dCs/dt = -kmpC_{SOIL} + h$ ....(4)

Where, C_{SOIL} = concentration of organic C in soil; t = time; k = first-order decomposition coefficient; m, p = correction factors for soil temperature and moisture; h = additional rate independent of decomposition rate such as erosion, deposition or net primary production.

One of the most significant changes, which occur with soil during transport, is change of texture of sediment relative to the soil from which it originates due to sorting of material. It has been shown that soil texture affects the mineralization of labile fraction of SOM and has an influence on transformation of labile SOM into slow and recalcitrant SOM (Vanveen *et al.,* 1984).

The SOM decomposition process in soil depends on soil depth. Temperature and moisture reduction coefficients (Voroney *et al.,* 1981) are included in SOM transformation equation (Eq. 4) to accommodate for the differences in these variables with soil depth. Majority of SOM dynamics models treat soil profile as a combination of layers with different decomposition rates (Molina and Smith, 1998). This subdivision on layers has an effect on how erosion component of the model operates. A scheme was proposed (Schimel *et al.,* 1985b; Bouwman, 1989) in which the upper soil layer, which becomes thinner due to the loss of soil, is compensated from the second layer. An amount of soil equal to the one lost to erosion is transferred from the second (lower) soil layer into the first (upper). As a result, the SOM in the upper layer becomes diluted.

Enrichment ratio of SOM in sediment is usually logarithmically related to sediment loss (Massey and Jackson, 1952; Ghadiri and Rose, 1991b)

$Er = bA^d$ ....(5)

Where, Er = enrichment ratio; n, d = dimensionless coefficients A= soil loss (t ha^{-1}).

Coefficients n and d vary widely with type and texture of soil, which complicates the incorporation of the logarithmic equation into erosion component of SOM dynamics models. Many models use constant values for enrichment ratio (Voroney *et al.,* 1981; Bouwman, 1989;), because sediment delivery is estimated as an average annual sediment yield (such as by USLE), while for the logarithmic relationship to be employed, sediment yield data for a specific event is needed. Logarithmic relationship is used in models such as CREAMS (Silburn and Loch, 1989) and EPIC (Williams, 1975) which have more powerful hydrological component capable of generating stochastic events. Because rare large storms are responsible for most of the soil loss from watersheds (Edwards and Owens, 1991), logarithmic expression for Er needs to be incorporated into SOM dynamics models. Enrichment ratio also tends to decrease with the rainfall duration (Palis *et al.,* 1997) in a logarithmic fashion.

The change in C budget over time on eroding site can be generalized as follows (Harden *et al.,* 1999)

$dC_S /dt = C_{NPP} - k_s C_{SL} - k_E C_{EROS} + C_{LHZ}$ ......(6)

Where, C_{NPP} = net primary production (input) of C; CSL= amount of C in the top layer of soil; C_{EROS} = amount of C eroded from the site; C_{LHZ} = amount of C, which is incorporated into upper layer from the lower layer of soil; k_S and k_E = decomposition rates of soil and sediment C. Monreal *et al*. (1997) demonstrated using Century model that erosion rate on Chernozemic and Gray Luvisolic soils was linearly correlated with SOM change. Similar trend was also observed in field measurements of SOM and soil losses for two watersheds in Ohio (Starr *et al.,* 2000). Monreal *et al*. (1997) estimated that depending on management practice 12–46 years was required to achieve steady-state level of SOM when erosion was included into simulation, which was 5–50% longer when erosion component was not included. Simulated SOM losses were in agreement with those obtained directly assuming 1.18 SOM enrichment factor.

Erosion and watershed carbon balance

Soil erosion results in drastic modifications to the structure as well as the biological and chemical properties of the soil matrix, affecting its productive capacity and ability to sequester atmospheric CO_2. Erosion affects watershed-level C balance by changing the magnitude of opposing C fluxes of (a) C input rates and (b) decomposition and stabilization.

Carbon input rates

Generally, unless the soil is eroded beyond a critical level, NPP on eroding slopes continues, albeit at a reduced rate if nutrients or water becomes limiting (Onstad *et al*., 1984). The newly assimilated C at eroded sites replaces, at least partially, C that was transported by erosion. As demonstrated by Harden *et al*. (1999), this dynamic replacement of eroded SOC is an important variable in maintaining the watershed-level C balance. This is especially important if NPP could be enhanced in eroding slopes with the use of supplements or best management practices, such as fertilization, irrigation, crop rotation, and reduced tillage. In the depositional part of a watershed, the C input is derived not only from fresh plant residue growing *in situ* but also from deposition of laterally flowing, eroded C. The rate of NPP in depositional basins is likely to be high, because the deposited topsoil provides additional organic matter, essential nutrients, and water-holding capacity.

Decomposition and stabilization

Soil erosion and deposition can speed or slow the decomposition of SOC at different parts of a watershed. At eroding slope positions, erosion can increase the rate of decomposition by breaking down aggregates (because of rain intensity or shearing during transport) and exposing organic matter that was previously encapsulated and physically protected from microbial and enzymatic degradation. On the other hand, removal of topsoil material from the eroded site exposes subsoil material, typically with less C content than topsoil, and therefore lowers the rate of decomposition. During transport, however, the decomposition of upland SOC can be enhanced, since the eroding material has the potential for further disturbance. For example, in arable lands, if transport rates are slow enough, eroded SOM can be decomposed through the breakdown of aggregates by tillage. Therefore, conceptually, the net impact on the CO_2 budget depends on the residence times of both the sediment and C (Harden *et al*., 1999). The extent to which soil erosion results in net enhancement of the SOC decay rate is still being debated. The estimates of the SOC fraction that is oxidized during erosion range from 0 to 100% (Beyer *et al*., 1993; Lal 1995; Jacinthe and Lal, 2001; Smith *et al.,* 2001; Oskarsson *et al.,* 2004). At depositional settings, the rate of decomposition of eroded SOC can be reduced by a combination of processes. Some of these processes are biochemical (recalcitrance of organic constituents), physical (protection with burial, aggregation, and changing water, air, and temperature conditions), and chemical (mineral–organic matter associations). Regardless of the rate of SOM oxidation, detachment and transport of soil particles modify the biochemical makeup of the SOC that reaches the depositional basins. During transport, the labile SOC fraction decomposes quickly, leaving behind a larger fraction of relatively more recalcitrant SOC, compared with the SOC that originates from the eroding hillslope profiles. In addition, inevitable losses (e.g., leaching and mineralization) further reduce the amount and, moreover, change the chemical recalcitrance of the deposited SOC after it arrives at the depositional settings. During intensive storm events, however, large loads of sediment can be moved from upper slopes directly to lower slope positions and streams. Indeed, it is possible that most of the stream sediment is moved during such events. With such rapid transport, it is likely that eroded C has little chance to be decomposed and reworked during transport, and that a significant fraction of labile C can enter depositional basins. In this scenario, eroded C remaining near the surface of lowlands could contribute to enhanced decomposition, while the decomposition rate of the eroded C that is buried at the depositional settings is likely to be reduced. The role of burial during sedimentation is key to the sink versus- source question for eroded C. Decomposition is generally accepted to be slower in the buried sediments of depositional basins than in the source profiles in the eroding slopes. This is partly because deposition of eroded C down slope is often accompanied by increased water content, reduced oxygen availability, compaction, and physical protection within inter- or intra-aggregate spaces that collectively can retard the decomposition rate of buried SOC. Indeed, SOC may be preserved and have much longer residence time in anoxic or suboxic floodplains, riparian ecosystems, reservoirs, or peat lands, compared with aerobic soils in upper watershed positions. Post-deposition (diagenetic) remobilization and transformations also are reduced in wetter depositional basins, favoring SOC preservation over mineralization (Gregorich *et al.,* 1998; Stallard, 1998; Harden *et al.,* 1999; McCarty and Ritchie, 2002) since anoxic or suboxic conditions reduce the rate at which soil microorganisms decompose organic matter (Jacinthe *et al.,* 2001). Furthermore, burial facilitates chemical and mineralogical transformations that contribute to C stabilization. With time, newly weathered, precipitated, or transported reactive mineral particles come in contact with buried C. These mineral particles provide surface area for the chemical stabilization of buried C, allowing the physically protected, labile SOC to form stable or metastable complexes with the mineral surfaces, thereby further slowing down its turnover. Moreover, during deposition, low-lying native soils are buried by erosion, potentially resulting in a significant reduction of native SOC decomposition (Liu *et al.,* 2003). Consequently, burial (in most cases) represents a net C sink, because it constitutes transfer of SOC from more active components in plant biomass and topsoil with short mean residence time (typically less than a century) to more passive reservoirs in adjacent depositional basins (Smith *et al.,* 2001), where C is physically protected from near-surface environments (Harden *et al*., 1999, Jacinthe *et al.,* 2001). In summary, the increased C input and reduced decomposition (stabilization) usually result in increasing the overall C stock in a watershed with erosion and deposition.

Opportunity in degraded lands

Improving agricultural and land-use policies in degraded lands, such as marginal land and eroding landscapes, offers an enormous opportunity for enhancing C sequestration. Proper soil conservation practices that maintain vegetative cover and enhance plant productivity can promote higher SOC input and storage. Because soil C in eroded, marginal lands is generally depleted by the past history of erosion or intensive land use, minimum tillage or fallow conditions (with a cover of vegetation) which are likely to increase the soil's potential to store C. For example, it is estimated that, in some regions, an increase in C storage of 0.2 to 2.2 metric tons per hectare per year may be observed with sustainable soil and water management (McCarty and Ritchie, 2002). Realization of this potential would have significant benefits by reducing atmospheric build-up of CO_2. Moreover, protecting depositional C from oxidation through minimal tillage increases the potential for sequestration. The dependence of NPP and C sequestration on rates of erosion and deposition for sites with and without conservation measures is shown schematically in figure 5. If we consider eroding and depositional parts of a watershed separately, under given erosion scenario, as soil erosion increases, NPP decreases; but the C sequestration potential of the soil increases, at least initially, because of the enhanced ability of the degraded upland soils to take up more C compared with undisturbed and undegraded sites (McCarty and Ritchie, 2002). Similarly, at the depositional sites in a given scenario (for example, alluvial plain), actual C sequestration follows a pattern similar to what it was at the eroding site, but with a higher rate of sequestration and a smaller decline after the peak, because the depositional sites continue to receive C-rich eroded soil. The added input of nutrient-rich topsoil at the depositional sites contributes to the maintenance of higher NPP. In the erosion and deposition conditions, proper soil and water conservation measures maintain or increase NPP. If NPP increases at the eroding site, C sequestration in the eroding soils is enhanced and maintained at a higher level, and the depositional sites have the capacity to increase C sequestration until a saturation point is reached. The absence of tillage and other anthropogenic disturbances is critical to achieving the conservation conditions as described in figure 5. On a cautionary note, marginal lands are vulnerable by definition, and

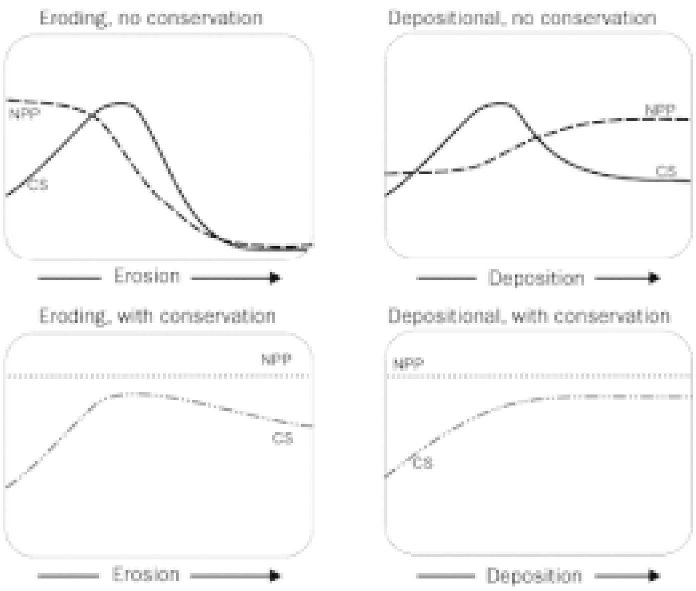

Fig 5 Conceptual relationship between soil erosion and deposition, net primary productivity (NPP), and carbon sequestration (CS) under given erosion and deposition scenarios

C sequestration is not permanent. Most of the C stored in floodplains or reservoirs is protected physically by aggregation or burial, and potentially can be mineralized easily at a more rapid rate than it was accumulated if the depositional basins are disturbed by practices such as dredging or dismantling of impoundments.

Conclusions

Minimizing soil erosion is vital to protecting natural resources, because accelerated erosion reduces soil quality and depletes the soil resource. Similarly, proper management of already degraded, marginal areas could ensure the environmental benefits of C sequestration resulting from burial and partial replacement of eroded SOC. Clearly, this benefit of erosion constituting a C sink is not a reason to relax erosion prevention measures; rather, it is an impetus for enhanced management of marginal (erosional and depositional) lands. Indeed, any such provision must ensure against incentives that might foster soil erosion. Erosion creates significant, formerly uncounted C sinks; thus there is a major need to better understand the C-sink potential of erosion in buried soils, and the processes that slow the turnover of buried C in alluvial and colluvial soils in different regions. The scientific uncertainty surrounding the fate and dynamics of eroded SOC after terrestrial sedimentation (in buried colluvial deposits and in aerated and waterlogged, submerged alluvial deposits), coupled with the potential for active management of these marginal systems, makes this a high-priority research area for global and regional C-cycle studies. Soil erosion and deposition most likely stabilize at least 0.72 Pg C per year globally. At the watershed level, this amounts to between 0.2% and 2.2% of NPP and about 16% of eroded C. Regardless of the small magnitude of C stabilization compared with NPP or with the C erosion rate, partial replacement of eroded C by new photosynthate, and stabilization of deposited C, very likely offsets up to 10% of the 2005 global fossil fuel CO_2 emissions. The contribution of deposition, terrestrial sedimentation, changes in soil properties at different lowland depositional sites depends on the nature of soil derived from upslope. The transported nutrient- and carbon-rich topsoil contributes an improvement in overall quality of the soil in depositional basins. Moreover, burial (after subsequent deposition) in different low lying depositional basins tends to be accompanied by higher proportion of fine soil particles (clay and fine silt).

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Carbon Sequestration in Forests and its Potential in Climate Change Mitigation

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Introduction

Active absorption of atmospheric carbon dioxide (CO_2) from the atmosphere through photosynthesis and its subsequent storage in the biomass of growing trees or plants is referred to as carbon sequestration (Baes *et al.*, 1977). Leaves utilise the atmospheric CO_2 for the manufacture of food in the form of glucose, which later gets converted into starch, lignin, hemicelluloses, amino acids and proteins; and directed to other components for storage. A number of factors such as temperature, rainfall, soil type and quality, biotic components like microbial growth, predation, pollination etc. influence the carbon sequestration rate of trees. Topographical features and human disturbances are also important factors (Ram Newaj *et al.*, 2010) for carbon sequestration rates. To determine the role of trees in mitigating atmospheric CO_2 content, it becomes essential to have accurate inventory of carbon content in trees. The issues of rise in atmospheric CO_2 coupled with rise in temperature and global warming have received the attention of scientists, resource managers, policy makers and public towards the upcoming climate change. Thus, it becomes imperative to harness the effective potential of plants for enhanced atmospheric CO_2 absorption.

Greenhouse Gases and Global Climate Change

Changes in Earth's temperature have been associated with atmospheric greenhouse gases (GHGs) levels in the atmosphere. The biophysical process altering Earth's natural "greenhouse effect" begins when GHGs in the atmosphere that allow the Sun's short wavelength radiation to pass through and absorbed by the Earth's surface and a part of it is re-emitted as long wavelength radiation. These GHGs trap the heat in the atmosphere (Leggett, 2007). Greenhouse gases affected by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and certain fluorinated compounds—chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), perchlorofluorocarbons (PFC), and sulfurhexaflouride (SF_6).

GHGs have different atmospheric lives. For example, water vapor generally lasts a few days, methane lasts approximately 12 years, nitrous oxide 114 years, and sulfur hexafluoride 3,200 years; carbon dioxide's atmospheric life varies (Bjorke and Seki, 2005). GHGs are compared in terms of global warming potentials (GWPs). GWPs estimate the pound-for-pound potential of a gas to trap as much energy as carbon dioxide (US EPA, 2007). The global warming potentials of some principal GHGs are: carbon dioxide (1), methane (23), nitrous oxide (296), hydrofluorocarbons (120 to 12,000), perfluorocarbons (5,700 to 11,900) and sulfur hexafluoride (22,200) (Gerrard, 2007).

Table 1 Worldwide GHGs emissions by economic sector, 2000

Sector	$MtCO_2$ eq.	Percentage (%)
Energy	24,722.3	59.4
Electricity	10,276.9	24.7
Transportation	4,841.9	11.6
Manufacturing	4,317.7	10.4
Other fuel combustion	3,656.5	8.8
Fugitive emissions	1,629.3	3.9
Land-use change and deforestation	7,618.6	18.3
Agriculture	5,603.2	13.5
Waste	1,465.7	3.5
Industrial processes	1,406.3	3.4
International bunker fuels	824.3	2.0
Total	41,640.5	100.0

(Source: Data from WRI, 2007)

Though the greenhouse effect is a naturally occurring process, but over the last 150 years this process has been exacerbated by increasing quantities of GHG emissions into the atmosphere; largely caused by burning fossil fuels. The greenhouse effect results in global climate change leading to socio-economic and environmental consequences (McCarthy *et al*., 2001).

The Carbon Cycle

CO_2 is cycled through four main global carbon stocks: the atmosphere, the oceans, fossil fuels, and terrestrial biomass and soils (Fig 1). According to Watson *et al*. (2000), over the period 1989-1998, activities in the energy and building sectors increased atmospheric carbon levels by 6.3 Gigatons of carbon per year (Gt C yr^{-1}). Land-use change and forestry (LUCF) activities released 60 Gt C yr^{-1} into the atmosphere

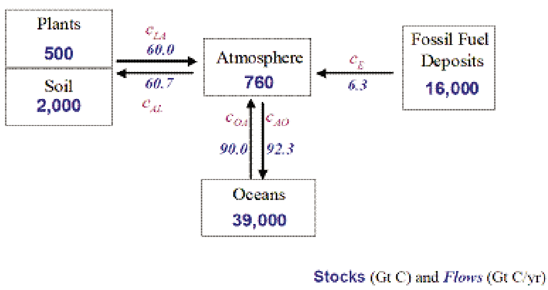

Fig 1 The global carbon cycle (Based on Watson *et al*., 2000)

and absorbed 60.7 Gt C yr^{-1} with a net effect of decreasing atmospheric carbon levels by 0.7 Gt C yr^{-1}. Oceans removed about 2.3 Gt C yr^{-1} from the atmosphere. The net result of these fluxes over the last 10 to 15 years is that atmospheric carbon levels have increased by about 3.3 Gt C yr^{-1}. Human activities release carbon as carbon dioxide by various means which alter carbon pools; the most important of these alterations is the transfer of carbon from its geologic pool to its atmospheric pool.

The rate C_{LA} includes emissions caused by respiration and deforestation, whereas C_{AL} includes carbon sequestered by afforestation and reforestation projects. Although the main contributor to mitigation of global warming will have to be the energy sector, mitigation can be achieved by decreasing C_{LA}, increasing C_{AL} or both. The balance of these exchanges is referred to as biological mitigation. Biological mitigation can occur through three strategies:

i. Conservation of existing carbon pools.
ii. Sequestration by increasing the size of existing pools.
iii. Substitution of sustainably produced biological products, such as using wood instead of energy-intensive construction materials, or using biomass to replace energy production from fossil fuels.

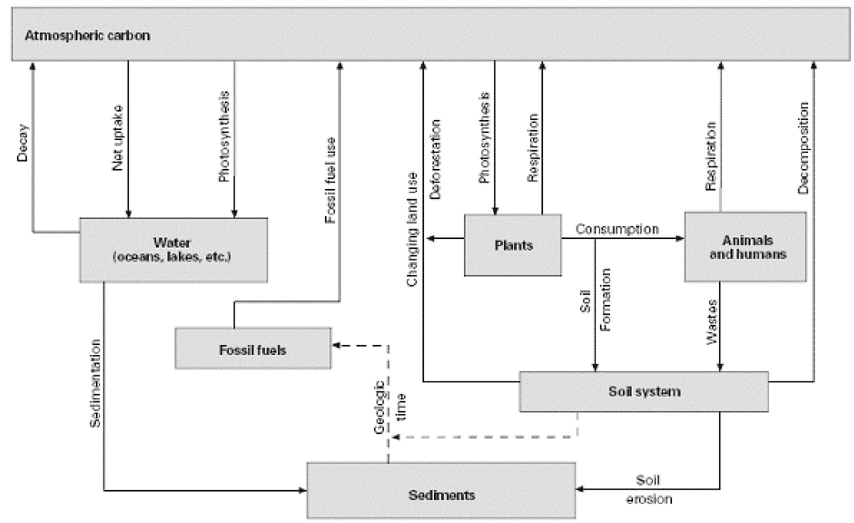

Fig 2 Carbon cycle aspects (Source: Mahdi Al-Kaisi, 2008)

The global potential of biological mitigation has been estimated at 100 Gt C (cumulative) by 2050, equivalent to about 10 to 20 per cent of projected fossil fuel emissions during that period (IPCC, 2001). The largest potential is in the subtropical and tropical regions, but realisation of this potential will depend on land and water availability and rates of adoption (Watson *et al*., 2000, IPCC, 2001). The large opportunities for biological mitigation in tropical countries cannot be considered in isolation of the broader policies onforestry, agriculture and other sectors. Barriers to reaching the potential level of mitigation include:

i. Lack of funding, and human and institutional capacity to monitor and verify mitigation efforts and outcomes.
ii. Food supply requirements.
iii. People living off the natural forests.
iv. Existing incentives for land clearing.
v. Population pressure.
vi. Switch from forests to pastures/agricultural lands.

Forest biomass and carbon pools

Forests play an important role in the carbon cycle because of photosynthesis. Photosynthesis is the basic process by which plants capture carbon dioxide from the atmosphere and transform it into sugars, plant fiber, and other materials. In the process of photosynthesis, trees and other plants take CO_2 from air, and in the presence of light, water, and nutrients, manufacture carbohydrates that are used for metabolism and growth of both aboveground and below-ground organs, such as stems, leaves, and roots. Concurrently, with taking in CO_2, trees utilize some carbohydrates and oxygen in metabolism and give off CO_2 in respiration. When vegetation dies, carbon is released to the atmosphere. This can occur quickly (in a fire), slowly (as fallen trees, leaves, and other detritus decompose), or extremely slowly (when carbon is sequestered in forest products). In addition to being sequestered in vegetation, carbon is also sequestered in forest soils. Soil carbon accumulated as dead vegetation is added to the surface or as roots added to the soil. Soil carbon is slowly released to the atmosphere as the vegetation decomposes (Gorte, 2007).

Forest soils can sequester 20 to 60 million tonnes of atmospheric methane per year, equivalent to 400 to 1,300 million tonnes of carbon (Reay *et al*., 2001). Soil microbes capture atmospheric methane in a process known as methane oxidation. Research has shown that forest soils are more effective than other land uses in storing methane, particularly in the well-aerated soils of temperate forests, and that the conversion of forest to other uses reduces methane oxidation. Methane oxidization also diminishes with increased soil moisture, such as in wetlands and peat lands, which tend to be methane sources (Bradford *et al*., 2001). Forest vegetation also plays a vital role in affecting surface temperatures through its surface albedo. Forests tend to have a lower albedo than other land uses and thus reflect less shortwave radiation into the atmosphere, thus reducing atmospheric temperatures.

Carbon pools in forest ecosystem have classically been split into five main categories: living above-ground biomass (AGB), living below-ground biomass (BGB), dead organic matter (DOM) in wood, DOM in litter and soil organic matter (SOM). A carbon source is a carbon pool from which more carbon flows out than flows in; while a carbon sink is one where more carbon flows in than out. Forests can switch between being a source (processes of decay, combustion and respiration) and a sink (process of tree growth and resultant biological carbon sequestration) of carbon over time (Brown, 2002).

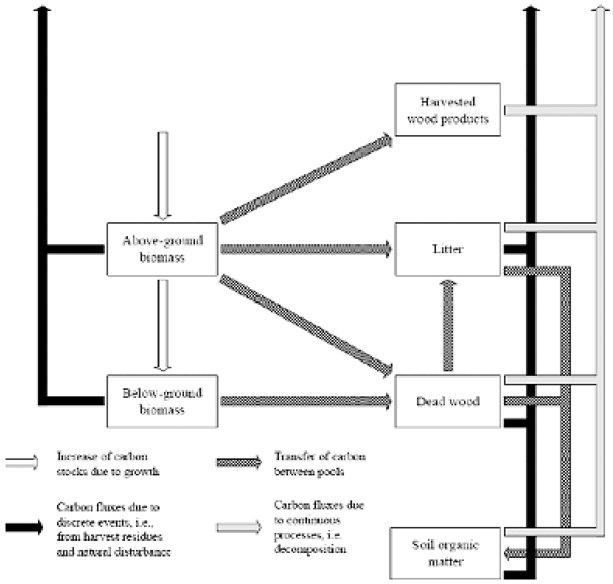

Fig 3 Generalised flow of carbon between pools (Source: IPCC, 2006)

Trees often represent the greatest fraction of total biomass of a forested area; with other carbon pools only a fraction of the total tree biomass. The understorey is estimated to be equivalent to 3%, dead wood 5-40%, and fine litter only 5% of that in the above-ground tree biomass. AGB in trees also responds more rapidly and significantly as a result of land-use change than other carbon pools. As a consequence, majority of the carbons accounting efforts are focused on tree AGB, for which there is considerable forest science research base.

As the most efficient natural land-based carbon sink, forests play an important role in global carbon cycling. Table 2 gives the potential of various biomes for carbon sequestration. The world's forests cover of 4,100 million hectares (Mha) contains 80 percent of all above-ground carbon (Dixon *et al*., 1994). The greatest threat to forests is the land-use change and deforestation in the tropics, which contribute about 18 percent of global greenhouse gas emissions (Stern *et al*., 2006). Consequently, forests are critical to stabilizing carbon dioxide and oxygen in Earth's atmosphere. Globally, forest vegetation and soils contain about 1,146,000 million tonnes (Mt) of carbon, with approximately 37 percent of this carbon in low-latitude forests, 14 percent in mid latitudes, and 49 percent at high latitudes (Dixon *et al*., 1994). Changes in carbon sequestration and storage over time have been due to changes in land use and land cover, particularly from forest to agriculture and more recently changes are due to conversion from forest to urban development, dams, highways, and other infrastructure.

Table 2 Categorisation of biomes and their C sequestration (CS) potential

Biomes	Primary method to increase Carbon Sequestration*	Potential CS (Pg C per year)
Agricultural lands	Management (H)	0.85–0.90
Biomass croplands	Manipulation (H)	0.50–0.80
Grasslands	Management(M)	0.50
Rangelands	Management (M)	1.20
Forests	Management (M)	1–3
Urban forests and grasslands	Creation and maintenance (M)	Not available
Deserts and degraded lands	Manipulation (H)	0.80–1.30
Terrestrial sediments	Protection (L)	0.70–1.70
Boreal peatlands and wetlands	Protection (L)	0.10 to -0.70
Total		5.65–10.10

(Source: DOE, 1999)
* The primary method of carbon sequestration is rated as high (H), medium (M), and low (L) levels of sustained management intensity required over the long term. Global potential sequestration rates were estimated that might be sustained over a period of 25–50 years.

In evaluating the capacity of trees and forests to sequester and store carbon, the important metric is net carbon uptake and storage. As the chemical reactions of respiration are temperature driven, increase in air temperature critically affects net uptake and storage of carbon. Studies on Douglas fir and pine trees in Washington and California have shown that net CO_2 uptake is markedly lower in midday under conditions of summer stress, when temperatures are high and water content in both air and soil is low (Helms, 1965). Thus, climate change will lower the capacity of plants to have positive net gains in carbon uptake, which could contribute to changes in forest type boundaries.

Net rates of CO_2 uptake by broad-leaf trees are commonly greater than those of conifers, but because hardwoods are generally deciduous while conifers are commonly evergreen, the overall capacity for carbon sequestration can be similar. Mixed-species, mixed-age stands tend to have higher capacity for carbon uptake and storage because of their higher leaf area. The capacity of stands to sequester carbon is a function of the productivity of the site and the potential size of the various pools, including soil, litter, down woody material, standing dead wood, live stems, branches, and foliage. In part, this is related to the capacity of stands to grow leaf area: more the leaves greater the stand capacity for photosynthesis and biomass production, but also the greater loss of CO_2 in respiration. Other stand dynamics that can influence sequestration capacity include age class distribution and shade tolerance. In the long run, stands of shade-tolerant species growing on high-quality sites typically have more leaf area, grow more wood, and sequester more carbon than stands of light demanding species. On similar sites, stands of light demanding species initially have higher rates of wood production and carbon sequestration, which culminate earlier but do not grow as much wood, as shade-tolerant species. The rate of CO_2 uptake by trees and stands is primarily a function of species, site quality, temperature, and availability of water and nutrients. Young trees and young stands have higher rates of carbon sequestration but lower levels of total amount stored; older trees and older stands have lower rates of net uptake because, as trees age, mortality and respiration are higher. However, older stands have higher carbon storage, provided carbon is not lost to insect depredations or wildfire.

Forests also release carbon and can become net sources of carbon to the atmosphere, particularly after a disturbance or in newly regenerated stands when soils are exposed during harvesting and site preparation. After disturbance, heterotrophic soil respiration is greatest in young forests and declines as forests age. Pregitzer and Euskirchen (2004) reported that mean temperate net ecosystem productivity in forests of 0–10, 11–30, 31–70, 71–120, and 121–200 years age was 1.9, 4.5, 2.4, 1.9, and 1.7 Mg C ha^{-1} yr^{-1}, respectively. As forests become older, the amount of carbon released through respiration and decay can exceed than that is taken up in photosynthesis; and the total accumulated carbon levels off. This situation becomes more likely as stands grow overly dense and lose vigor, and it will become more probable in areas where climate change causes higher temperatures. However, as maturing forests become less productive, they may continue to accumulate carbon in coarse woody debris, the forest floor, and the soil.

Wildfires act as the greatest cause of carbon release. The amount of carbon released by wildfires is difficult to estimate because of the great variability in fire intensity and fuel loads. It is estimated that burning of one ton of every forest biomass releases roughly 1.3 to 1.5 tonnes of CO_2, 0.05 to 0.18 tonnes of carbon monoxide, and 0.003 to 0.01 tonnes of CH_4 (Sampson, 2004). Other important forest disturbances include tree mortality caused by insects and disease, hurricanes, ice storms, droughts, and floods.

Data acquisition for forest carbon accounting

Forest carbon accounting can be done by collating of existing national, regional or global data. At a national level, forest inventories, woody biomass assessments, agricultural surveys, land registry information and scientific research can prove useful for land classification and model parameters. Data on temperature, rainfall, soil type and topography should also be sourced at smaller scales. In particular, data sources will include national statistical agencies, sectoral experts and universities. Global and regional level data is also valuable for forest carbon accounting. International land-use and land cover datasets exist, largely from remote sensing imagery, although image resolution and the accuracy of ground-referenced data are generally limited. Sources of data include international experts, international organisations publishing statistics, such as the United Nations and OECD, and international scientific journals. In particular, the FAO Forest Resources Assessment (FAO, 2006), the IPCC Agriculture, Forestry and Other Land Use (AFOLU) inventory guidance volume (IPCC, 2006), and FAO's primer for estimating biomass (Brown, 1997), all provide parameter information that can be used in carbon accounting.

The IPCC presents a multi-tiered approach to emissions accounting. Generally, Tier 1 reporting requires very little primary data collection to generate estimates of forest biomass. IPCC guidance reports a number of parameters and emission factors that can be applied, based on region-specific climate and vegetation data. Table 3 presents estimated forest biomass values and annual growth increments in biomass by region and forest types. Tier 2 also utilises default forest biomass information, but in combination with country-specific data. Tier 3 uses highly detailed localised data, often with repeated measures of permanent forest sample plots.

Table 3 Default forest biomass and annual biomass increment under Tier 1 IPCC guidance

Climate Domain	Ecological zone	AGB in natural forest (t ha^{-1})	AGB in forest plantation (t ha^{-1})	AGB growth in natural forest (t $ha^{-1}yr^{-1}$)	AGB growth in forest plantation (t $ha^{-1}yr^{-1}$)
Tropical	Tropical rain forest	300	150	7.0	15.0
	Tropical moist deciduous forest	180	120	5.0	10.0
	Tropical dry forest	130	60	2.4	8.0
	Tropical shrub land	70	30	1.0	5.0
	Tropical mountain systems	140	90	1.0	5.0
Subtropical	Subtropical humid forest	220	120	5.0	10.0
	Subtropical dry forest	130	60	2.4	8.0
	Subtropical steppe	70	30	1.0	5.0
	Subtropical mountain systems	140	90	1.0	5.0
Temperate	Temperate oceanic forest	180	160	4.4	4.4
	Temperate continental forest	120	100	4.0	4.0
	Temperate mountain systems	100	100	3.0	3.0
Boreal	Boreal coniferous forest	50	40	1.0	1.0
	Boreal tundra woodland	15	15	0.4	0.4
	Boreal mountain systems	30	30	1.0	1.0

(Source: IPCC, 2006)

Remote sensing is useful in forest carbon accounting for measurement of total forest area, forest types, canopy cover and height, and branch surface to volume ratios. Once imagery has been acquired, expertise is necessary to match remotely sensed data to land-cover categories. These land cover categories then require field data, from either existing or newly acquired studies, to estimate carbon stocks for each category; this is known as 'ground-truthing'. Remote sensing is also limited where there are seasonal forest types, where there is substantial cloud cover (not such a problem for radar), and in the monitoring of degradation of forest (particularly where dense canopy hides below-canopy activities). Where a time-series of images exist, remote sensing is also useful for assessing changes in forest area and providing baselines for project emission reductions accounting. Similarly, it has been promoted for long-term monitoring, reporting and verification for emission reductions targets. Remote sensing is replicable, standardised globally, implemented at a national level and is stable over the long term (UN-REDD, 2008).

Actual field data is preferable to default data for forest carbon accounting and is required to verify remotely sensed information and generalised data sets. Gathering field measurements for forest carbon accounting requires sampling as complete enumerations are neither practical nor efficient. For carbon inventory purposes, stratified random sampling yields more precise estimates (MacDicken, 1997). Forest areas should be stratified according to objectively chosen variables, with random sampling within stratifications so as to adequately capture variation. It is also important to choose an appropriate number of sample plots and there are commonly understood relationships between sampling error, population variance and sample size. Provisional surveys and/or existing data can be utilised to establish sample sizes and tools also exist to calculate sample sizes based on fixed precision levels or given fixed inventory costs (MacDicken, 1997). Where carbon stocks and flows are to be monitored over the long term, permanent sites should be considered to reduce between-site variability and to capture actual trends as opposed to short term fluctuations (Brown, 2002).

Accounting for forest carbon stocks

Above-ground biomass (AGB)

The AGB carbon pool consists of all living vegetation above the soil, inclusive of stems, stumps, branches, bark, seeds and foliage. For accounting purposes, it can be broadly divided into that in trees and that in the understorey. The most comprehensive method to establish the biomass of this carbon pool is destructive sampling, whereby vegetation is harvested, dried to a constant mass and the dry-to-wet biomass ratio established. Destructive sampling of trees, however, is both expensive and somewhat counter-productive in the context of promoting carbon sequestration. Two other approaches for estimating the biomass density of tree biomass exist and are more commonly applied. The first directly estimates biomass density through biomass regression equations. The second converts wood volume estimates to biomass density using biomass expansion factors (Brown, 1997).

Where stand tables – the tally of all trees in a particular diameter class – are available, the biomass per average tree of each diameter class of the stand table can be estimated through biomass regression equations, also called allometric equations. Allometric equations have the general form, Tree biomass (B) = $f(V1, V2,...,Vn)$, the independent variables (Vi) may include diameter at breast height (D), height (H) and wood density (ñ) (Ketterings *et al*., 2001).

Alternatively, the results of direct sampling of tree diameter in the area of interest can be used in these regression equations. The total biomass of the forest stand is then derived from the average tree biomass multiplied by the number of trees in the class, summed across all classes. In both tropical and temperate forests, such diameter measurements explain more than 95% of the variation in tree biomass (Brown, 2002)

Table 4 Allometric equation for estimating fresh biomass (kg tree^{-1}) of different agroforestry trees

Growing habit	Tree species	Allometric equation
Fast	*Eucalyptus tereticornis*	$y=e(a+b/dbh^{1.5})$, a=6.15, b=-78.97
	Albizia procera	$y=0.525(dbh)^{2.014}$
Medium	*Azadirachta indica*	$y=0.904(dbh)^{1.760}$
	Acacia nilotica	
	Butea monosperma	
	Dalbergia sissoo	
	Anogeisus pendula	
Slow	*Emblica officinalis*	$y=2.994(cd)^{1.285}$

y= biomass in kg; dbh= diameter at breast height (cm); a and b are constants; cd= collar diameter

(Source: Rajendra Prasad *et al*., 2010)

There are a number of databases and publications that present default regression equations, stratified by rainfall regime and region. These default equations, based on a large sample of trees, are commonly applied for generation of the local allometric equations. However, application of default equations will tend to reduce accuracy of the biomass estimate. However, as elevation increases potential evapo-transpiration decreases and the forest are wetter at a given rainfall. Thus, a regression equation developed for lower elevation but applied to highland forest which may give inaccurate biomass estimates.

Where information on the volume of wood stock exists such as from commercial inventories, biomass density can be estimated by expanding the merchantable volume of stock, net annual increment or wood removals, to account for biomass of the other above-ground components. To do this, either Biomass Expansion Factors (BEFs) or Biomass Conversion and Expansion Factors (BCEFs) are applied. BEFs expand dry wood stock volume to account for other non-merchantable components of the tree. To establish biomass, the volume must also be converted to a weight by multiplication of the wood density as well as the BEF. In contrast, BCEFs use only a single multiplication to transform volume into biomass; this is useful where wood densities are not available. However, unless locally-specific equations exist to convert direct measurements of tree height and diameter to volume, regression equations to directly estimate biomass from tree diameter are preferable (IPCC, 2003).

With the tree component of a forest, the major fraction of biomass, the understory, is often omitted from accounting. This omission results in a conservative carbon stock estimate but is justified only in areas where trees are present in high density; neglecting the shrub layer in open woodlands, savannah or in young successional forest may significantly underestimate carbon density.

Below-ground biomass (BGB)

The BGB carbon pool consists of the biomass contained within live roots. Regression equations from root biomass data have been formulated which predict root biomass based on above-ground biomass carbon (Brown, 2002; Cairns *et al*., 1997). Cairns *et al*., (1997) reviewed 160 studies covering tropical, temperate and boreal forests and found a mean root-to-shoot (RS) ratio of 0.26, ranging between 0.18 and 0.30. Although roots are believed to depend on climate and soil characteristics (Brown & Lugo, 1982), Cairns *et al*. (1997) found that RS ratios were constant between latitude (tropical, temperate and boreal), soil texture (fine, medium and coarse), and tree-type (angiosperm and gymnosperm). To avoid measuring roots, a conservative approach recommended by MacDicken (1997) is to estimate root biomass at no less than 10 per cent or 15 per cent of the above-ground biomass. Hamburg (2000) recommends a default RS ratio for regrowing forests of 0.15 in temperate ecosystems and 0.1 in tropical ecosystems. BGB can also be assessed locally by taking soil cores from which roots are extracted; the oven dry weight of these roots can be related to the cross-sectional area of the sample, and so to the BGB on a per area basis (MacDicken, 1997).

Dead organic matter (wood)

The DOM (wood) carbon pool includes all non-living woody biomass and includes standing and fallen trees, roots and stumps with diameter over 10 cm. Often ignored, or assumed in equilibrium, this carbon pool can contain 10-20% of that in the AGB pool in a mature forest (Delaney *et al*., 1998). However, in immature forests and plantations, both standing and fallen dead wood are likely to be insignificant in the first 30-60 years of establishment. The primary method for assessing the carbon stock in the DOM wood pool is to sample and assess the wet-to-dry weight ratio, with large pieces of DOM measured volumetrically as cylinders and converted to biomass on the basis of wood density, and standing trees measured as live trees but adjusted for losses in branches (less 20%) and leaves (less 2-3%) (MacDicken, 1997). Methods to establish the ratio of living to dead biomass are under investigation, but data is limited on the decline of wood density as a result of decay (Brown, 2002).

Dead organic matter (litter)

The DOM (litter) carbon pool includes all non-living biomass with a size greater than the limit for soil organic matter (SOM), commonly 2 mm, and smaller than that of DOM wood, 10 cm diameter. This pool comprises biomass in various states of decomposition prior to complete fragmentation and decomposition where it is transformed to SOM. Local estimation of the DOM litter pool again relies on the establishment of the wet-to-dry mass ratio. Where this is not possible, default values are available by forest type and climate regime from IPCC that ranges from 2.1 tonnes of carbon per hectare in tropical forests to 39 tonnes of carbon per hectare in moist boreal broadleaf forest (IPCC, 2006).

Soil organic matter (SOM)

SOM includes carbon in both mineral and organic soils and is a major reserve of terrestrial carbon (Lal & Bruce, 1999). Inorganic forms of carbon are also found in soil; however, forest management has greater impact on organic carbon. SOM is influenced through land use and management activities that affect the litter input, e.g., how much harvested biomass is left as residue, and SOM output rates, e.g. tillage intensity affecting microbial survival. In SOM accounting, factors affecting the estimates include the depth to which carbon is accounted (commonly 30 cm) and the time lag until the equilibrium stock is reached after a land use change (commonly 20 years). Accounting for SOM is more costly as local estimation of the carbon contained in this pool commonly relies on laboratory analysis of field samples. At sample sites, the bulk density of the soil and wet weight of the sample must also be recorded so that laboratory results can be translated into per unit area carbon stock. Hamburg (2000) suggested that by using a few generalized principles, it should be feasible to measure soil carbon to an acceptable level of accuracy for biological mitigation projects. Hamburg (2000) recommended that the soil carbon should be measured at least up to one metre of depth, and that measurements of soil carbon and bulk density be taken from the same sample.

Fortunately, for projects that are known to have non-decreasing effects on soil carbon, it may not be necessary to measure soil carbon after the baseline is established. Rates of soil oxidation (a process that releases CO_2) under different land uses are available (Brown, 2001). As a general rule, reforestation projects in agricultural or degraded land would tend to increase soil carbon. If the marginal cost of measuring this carbon pool is greater than the marginal benefit of the carbon credits obtained, it would be better off not measuring this pool.

Table 5 Carbon content (%), total dry biomass, carbon sequestration, equivalent CO_2 and CO_2 sequestration rates of different agroforestry trees (10 years old)

Tree species	Carbon content* (%)	Total dry biomass (kg tree^{-1})	Total C sequestered (kg tree^{-1})	Equivalent CO_2 (kg)	CO_2 removed from atmosphere (kg tree^{-1}year^{-1})
Eucalyptus tereticornis	42.07	154.59	65.03	238.42	23.84
Albizia procera	40.62	314.49	127.74	468.33	46.83
Azadirachta indica	41.05	71.14	29.20	107.07	10.70
Acacia nilotica	41.18	53.22	21.92	80.35	8.04
Butea monosperma	41.42	97.74	40.48	148.42	14.84
Dalbergia sissoo	40.01	106.31	42.53	155.94	15.59
Anogeisus pendula	38.28	21.47	8.22	30.13	3.01
Emblica officinalis	39.16	32.40	12.69	46.51	4.65

* Carbon content (%) is the mean value calculated from stem, stem bark, branch, branch bark, foliage and root components of the trees. (Source: Rajendra Prasad *et al*., 2010)

Management approaches for enhancing storage and reducing emissions

Management of the forest resources should aim at providing ecological, social, and economic benefits to society in the face of the environmental stress associated with climate change. The first approach is adaptation, which involves positioning forests to become more healthy, resistant, and resilient. The second is mitigation, in which forests and forest products are used to sequester carbon, provide renewable energy through biomass, and avoid carbon losses due to fire, mortality, and conversion. On any given area of forest land, adaptation and mitigation objectives at the same time could be either complementary or incompatible. A complementary situation would occur where activities to maintain healthy, resilient forests tend to reduce the risk of uncharacteristically severe wildfire, CO_2 emissions, and damage to watersheds, and where the byproducts of such activities are used to offset fossil fuel burning. Incompatible competition could occur, for example, on some parts of national forests, where the objectives of sequestering high levels of carbon may conflict with adaptation needs that require reducing carbon stocks.

Adaptation

Three adaptive strategies based on understanding ecological processes rather than structure and function are currently discussed increasing resistance, increasing resilience, and assisting migration (Perschel *et al*., 2007; Millar *et al*., 2007).

Resistance is the capacity of an ecosystem to avoid or withstand disturbance, such as anticipated increase in insect and disease epidemics and wildfires. Management actions would aim at forestalling damage and protecting valued resources, such as water, endangered species, wildland, urban interface areas, and special forest stands. Treatments to be considered include thinning of overstocked stands, prescribed burning, removal of invasive species, and restoration of native species. It is important to identify which populations are most at risk and which areas are more likely to be buffered against the effects of changes in climate; and thus act as refugia.

Resilience is the capacity of an ecosystem to regain functioning and development after disturbance. Management actions would aim at retaining desired species even if sites become less optimal. Possible treatments include: i) promoting diversity in species and age classes when replanting or conducting other treatments after a disturbance event; ii) broadening genetic variability of seedlings while reforesting after harvesting, fires, or other disturbances; iii) supporting existing forest communities while allowing transitions to new forest types; iv) identifying and enhancing possible refugia prior to disturbance; v) enhancing landscape connectivity so that ecological movement can take place unimpeded across the landscape, including prevention of further forest fragmentation and restoration of ecosystem processes, such as watershed function and hydrologic processes.

To assist migration, forest management actions would seek to facilitate the transition of an ecosystem from current to new conditions. Consideration would be given to introducing different, better-adapted species, expanding genetic diversity, encouraging species mixtures, and providing refugia. This approach is highly controversial; it involves taking action based on modeling and other projections for which outcomes or expectations are highly uncertain—and is in a youthful stage of development (McLachlan *et al*., 2007). Assisted mitigation might be considered in several circumstances: i) where, after a fire or insect or disease outbreak, planting of the original species is predicted to fail; ii) on the edge of an ecotone where new species are known to be migrating into the area in a manner that validates the climate change models for the region; iii) for rare, threatened, or endangered species that are endemic to a small area and are expected not to be successful in migrating without assistance; iv) new species could be added to the mix of trees being planted if these are not expected to have negative ecological consequences; and v) where refugia have been identified as places to plant and "store" endangered species.

Mitigation

Marland and Schlamadinger (1999) reported that storing carbon in the forest and harvesting forests for a sustained flow of forest products are not necessarily conflicting options. Mitigating net emissions of carbon depends on site-specific factors, such as forest productivity and the efficiency with which harvested material is used. For some forest conditions, it is possible that early harvesting and use of wood products, could result in a lower rate of carbon accumulation compared with letting the forest grow to an older age before harvesting. Alternatively, focus on managing for carbon accumulation could lead to earlier harvest for some forest growth conditions. The degree to which forest management would change carbon sequestration and storage would also be influenced by whether wood use is long- or short-lived, whether the substitution offset is high or low, and whether there is high or low energy conversion efficiency.

Silvicultural treatments for forest carbon sequestration

Traditional silvicultural treatments focused on wood, water, wildlife, and aesthetic values that are fully amenable to being applied to enhancing carbon sequestration and reducing emissions from forest management (Helms, 1996). Various silvicultural aspects can be discussed as follows:

1. *Choice of management regime:* Even- or uneven- aged management regimes have variable carbon uptake characteristics over short time horizons, such as a rotation. By providing continuous canopy cover, uneven-aged management is likely to provide continuous carbon uptake, depending on the periodicity and intensity of partial harvest entries. In comparison, the carbon uptake under even-aged management is strongly influenced by rotation length and the length of regeneration periods when the stand has little canopy cover. Adaptive approaches with appropriate silviculture in each site as a mosaic across the forest enhance overall forest productivity and carbon uptake.
2. *Choice of species:* Initially, fast-growing, shade-intolerant species have higher rates of carbon sequestration at the younger age than more shade-tolerant, slow-

growing species. However, over time, shade-tolerant species are likely to have higher stand densities and leaf area, and therefore higher accumulation of carbon stocks. Mixed-species and mixed-age stands are likely to accumulate more carbon than single-species stands. Genetic selection, tree improvement, and biotechnology can enhance the rate of carbon uptake and storage by providing trees with higher net carbon uptake capacity. These trees are likely to have special application in growing short-rotation tree crops for bioenergy or cellulosic ethanol.

3. *Slash disposal:* Residues (tops, leaves, and branches) from harvesting can be evaluated for the extent to which various treatments affect the carbon balance. Allowing this material to decay and return nutrients to the soil is a carbon-neutral process, which takes several years; may increase the risk of wildfire. Burning the slash, although also a carbon- neutral process, immediately releases carbon, volatilized nitrogen, other greenhouse gases, and particulates into the atmosphere. Incorporating wood residues into the soil rather than burning it or leaving it to decay can increase or prolong carbon storage in the soil (Birdsey *et al*., 2006). Alternatively, depending on costs, this material could be used for bioenergy or the production of cellulosic ethanol. Removal of slash, however, may not be appropriate for sites with low productivity.
4. *Site preparation:* In the context of carbon sequestration, a major consideration is limiting the loss of soil carbon that follows exposure during such treatments, which may increase oxidation of soil carbon, temperature (which increases respiration of soil organisms), disturbance, and soil erosion. Site preparation that incorporates wood residues into the soil can increase or prolong carbon storage in the soil (Birdsey *et al*., 2006).
5. *Regeneration:* Whether by natural seeding, direct seeding, planting, or some mixture of treatments, regeneration should be done promptly to minimize the time soil is exposed and the canopy is open. Quick tree regeneration also reduces the risk for the site of being occupied by brush, which has lower leaf area and less CO_2-sequestering capacity than trees. Early brush control has been shown to have important leverage in improving wood-growing capacity and storing carbon in both the forest and stored products (CFR, 2007).
6. *Fertilizer:* Sometimes applied in planted forests and in short-rotation plantations, fertilizers increase rates of growth and leaf area production and therefore the rate of carbon uptake and sequestration. In carbon accounting, however, the source of materials used as fertilizers and the source and cost of energy used in manufacture, transportation, and application must be factored in.
7. *Thinning and partial harvesting:* Thinning and partial harvesting are techniques used in even- and uneven-aged management, respectively, to control stocking levels and stand density. The operations may be either pre-commercial (i.e., the thinned material is not merchantable) or commercial and are designed to improve

the growth of preferred trees. The basic concept is to allocate growth and leaf area among either a greater number of small-diameter trees or a fewer number of large-diameter trees. Both treatments make openings in the canopy, and in the context of carbon storage, it is preferable to conduct light, frequent thinning rather than heavy, infrequent thinnings. The latter creates larger openings in the canopy that require longer time to regain leaf area and capacity for carbon storage.

8. *Rotation length:* Rotation length in even-aged management influences carbon accumulation because longer rotations and larger trees increase on-site storage (In uneven- aged management, decisions on the maximum-sized tree follow the same logic). Longer rotations in even-aged management favor carbon accumulation because less time is taken up in reforestation and rebuilding the canopy. However, longer rotations can incur larger management costs as the value of growth rates of timber fall below the expected cost of money, and delay in harvesting reduces value from other uses, including carbon storage in wood products and substitution of wood for fossil-intensive products. Longer rotations and management cycles may also involve thinnings or partial cuts to maintain forest health.
9. *Expansion of forestland (afforestation):* One of the most widely recognized forestry practices for the mitigation of climate change is the afforestation of nonforested areas to increase sequestration and storage. Because forest is the most efficient land use for carbon uptake and storage, degraded areas that can be restored to a productive condition have a significant opportunity to sequester carbon. Whether the land was degraded by unsustainable practices or natural events, such opportunities may provide economic incentives to turn these areas back into productive forests.
10. *Managing for Carbon*: Shade intolerant species with high initial growth rates, grown at the highest stocking density and harvested at the culmination of mean annual increment, will sequester the most carbon in the shortest amount of time. This short rotation, even aged forest management regime, repeated in perpetuity with succeeding rotations of shade-intolerant trees, is often said to sequester the most carbon. Shade tolerant species can be grown at a higher stand density than light demanding species but have lower initial growth rates that culminate later; however, the overall amount of carbon sequestered per unit of forest area will be greater. Moreover, harvesting and site preparation activities will be less frequent and thus the associated carbon emissions will be lower. For continuous and overall maximum sequestration, mixtures of light demanding and shade-tolerant species would utilize all the photosynthetic niches in the forest canopy and forest understory while maintaining overall growth rates. Uneven- aged management would use a combination of individual tree selection, crown, and understory thinning, group selection, irregular shelterwood, and other intermediate cuttings to maintain a

mixture of different age classes of shade intolerant and loving tolerant trees. Again, emissions would have to be calculated for the frequent management entries, as would the combined mean annual increment for all the different species and age classes of trees, which must be discounted to an annual basis.

Conclusion

Changes in temperature and precipitation regimes have dramatically affected forests. The changes in temperature have been associated with increasing concentrations of atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere. Most familiar ways to reduce GHGs emissions and atmospheric concentrations are increasing energy efficiency and conservation, and using cleaner, alternative energy sources, while using forests to address climate change is less familiar yet equally essential. Unique among all possible remedies, forests can both prevent and reduce GHG emissions while simultaneously providing essential environmental and social benefits, including clean water, wildlife habitat, recreation, forest products, and other values and uses.

The capacity of stands to sequester carbon is a function of the productivity of the site and the potential size of the various pools—soil, litter, down woody material, standing dead wood, live stems, branches, and foliage. Forests of all ages and types have remarkable capacity to sequester and store carbon, but mixed-species, mixed-age stands tend to have higher capacity for carbon uptake and storage because of their higher leaf area. Ensuring full stocking, maintaining health, minimizing soil disturbance, and reducing losses due to tree mortality, wildfires, insect, and disease would enhance the sequestration capacity of the forest. Controlling stand density with appropriate silvicultural aspects by prudent tree removal provides renewable products, including lumber, engineered composites, paper, and energy, even as the stand continues to sequester carbon.

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Carbon Sequestration through Agroforestry

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Introduction

Globally, forests contain more than half of all the terrestrial carbon, and account for about 80% of the carbon exchange between terrestrial ecosystems and the atmosphere. Forest ecosystems are estimated to absorb upto 3 Pg (3 billion tones) of carbon annually. Decrease in deforestation helps to preserve current carbon reservoir and afforestation helps holding carbon for longer time. Anthropogenic activities have known to affect the biosphere through changes in land-use and forest management activities, thus altering the natural balance of greenhouse gases in the atmosphere. Over the last three centuries, forests have decreased by 1.2 billion hectares, i.e., 19% and grasslands by 560 million hectares. This has resulted due to increase in croplands and growth of urban areas. The rate of agricultural expansion during the period 1950-80 was greater than entire span of 150 years between 1700 and 1850. During the decade 1981-90, land-use changes in the tropics accounted for CO_2 emission of about 1.6 G t per year. On the other hand, terrestrial vegetation assimilated approximately 1.8 G t of carbon per year during the same period. In sum, the carbon balance shows that in the 1980s the terrestrial vegetation in the tropics acted as a net sink of carbon (Bhadwal and Singh, 2002). Carbon storage in the vegetation in India from the year 1880 onwards shows a decreasing trend. This situation warranted to identify and implement the best forestry/ agroforestry options, which fulfills the demand of wood and its products along with increasing carbon sequestration.

The probable effect higher CO_2 concentration in the atmosphere may increase plant photosynthesis and thus crop yield may increase (Kimball, 1983) and will increase net primary production in tropical forest ecosystems (Mingkul and Woodard, 1998). However, a rise in temperature may reduce crop yields by hastening plant development by modifying water and nutrient budgets and by increasing plant stress (Long, 1991). The net effect of increased CO_2 and climate change on crop yield thus depend on local conditions. While warmer summer air temperature might be beneficial to crop production in the temperate latitudes where the length of the growing season and frost-free period would increase, warmer temperatures exert negative effects on crop maturity in those regions where temperature and water stress limit crop production. Therefore, vast areas of the arid and semi-arid regions of India, where agriculture is mostly rainfed, strong adverse effects of global warming are probable. Lal *et al*. (2001) projected 5 to 25% decline in winter rainfall and 10 to 155% increase in monsoon rainfall over India during the 2080s, which is significant and may lead to droughts during the dry months and more intense rainfall spell during the wet season. On the other hand, agriculture is also a source of negative environmental impacts in some areas. Eutrophication, pesticides, pathogens, salts and eroded soils are leading causes of water quality problems in many parts of the world.

Carbon emission by India

About 30 gases produced by human activity have been identified as contributing to the greenhouse effect. The main ones are carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydroflurocarbon (HFCs), Perflurocarbons (PFCs) and Sulphur hexafluoride (SF_6). The contribution of carbon dioxide, methane and nitrous oxide is 55, 18 and 6%, respectively, of the overall global warming effect arising from human activities.

India currently ranks fifth in carbon emissions in the world, behind only the USA, China, Russia and Japan, and currently accounts for about 4.2% of the world's total fossil fuel-related carbon dioxide emissions. In the past decade alone, India's carbon emissions have increased by about 60% and are about nine times higher than they were forty years ago. Much of this increase is due to India's increasing utilization of its coal resources for power generation. Emission from coal made up 69% of the total emission in 2002 followed by petroleum at 27%. Carbon emissions are forecast to grow by about 3.3% annually through 2020.

Strategies for biological mitigation of climate change

Biological mitigation can occur through three strategies: (i) conservation of existing carbon pool; (ii) sequestration by increasing the size of existing pool; and (iii) substitution of sustainably produced biological products, such as using wood instead of energy intensive construction materials, or using biomass to replace energy production from fossil fuels. Option first and second result in higher carbon stocks but can lead to higher carbon emission in the future and option third can continue indefinitely (IPCC, 2001).

Potential of agroforestry in carbon sequestration

With adequate management of trees in cultivated lands and pastures, a significant fraction of the atmospheric C can be captured and stored in plant biomass and in soils. In agroforestry systems, C sequestration can be divided into two phases. At the establishment, many systems are likely to be source of GHGs (loss of C and N from vegetation and soil), then follow a quick accumulation phase and a maturation period when tons of C are stored in the boles, stems, roots of trees and in the soil. At the end of the rotation period, when the trees are harvested and land returned to cropping (sequential system), a part of the C would be released back to the atmosphere (Dixon *et al*., 1994). C storage can continue way beyond if boles, stem or branches are processed in any form of long lasting products (Roy, 1999). Therefore, effective sequestration can only be considered if there is a positive net C balance from an initial stock after a few decades (Felter *et al*., 2001).

The use of plant residues, mulching and animal manure, combined with conservation practices such as zero tillage (Feller *et al*., 2001) have been shown to increase soil C. Agroforestry trees also improve land cover in agricultural fields in addition to providing C inputs (root biomass, litter and prunings) to the soil. It has been speculated that the most significant increase in C stock occurs in fine-textured soils, where C is better protected through soil aggregation (Ingram and Fernandes, 2001). But, one must be aware of the fact that soils have a finite sink capacity of 0.4 – 0.6 Pg C yr^{-1} over 50-1000 years (Paustian *et al*., 2000; Ingram and Fernandes, 2001). If the above ground and soil C are considered together, 1.1 – 2.2 Pg C could be sequestered annually over 50 years, which, as estimates suggest, would offset about 10-15% of the current annual C emissions (Dixon, 1995). However, the implementation of agroforestry projects could be justified for many other reasons. First, increasing soil C greatly benefits agricultural productivity and sustainability. Second, given the improbability of obtaining any single mitigating method, adding modest contributions together appears to be a more realistic way of achieving CO_2 reduction targets (Paustain *et al*., 1997). Third, the financial cost of C sequestration through agroforestry appears to be much lower (approximately $1-69/ Mg C) than through other CO_2 mitigating options.

Present status of carbon stocking in different Agroforestry systems

Agroforestry may involve practices that favour the emission of GHGs such as shifting cultivation, pasture maintenance by burning, paddy cultivation, N fertilization and animal production (Le Mer and Roger, 2001). However, several studies have shown that the inclusion of trees in the agricultural landscape often improves the productivity of system while providing opportunities to create C sinks (Winjum *et al*., 1992; Dixon *et al*., 1993; Krankina and Dixon, 1994; Dixon, 1995). The amount of C sequestered largely depends on the agroforestry system put in the place, the structure and function of which are, to a great extent, determined by environmental and socio-economic factors. Other factors influencing carbon storage in agroforestry systems include tree species and system management. Table 1 shows the carbon storage potential of agroforestry systems in different regions of the world (Dixon *et al*., 1993; Krankina and Dixcon, 1994; Schroeder, 1994; Winjum *et al*., 1992).

Block plantation

Stand biomass of *Gmelina arborea* ranged from 3.94 (1 year old) to 53.67 t ha^{-1} (6 year old) and stand carbon in 6 year old plantation ranged from 24.12 to 31.12 t ha^{-1} at different sites (Swamy *et al*., 2003). Medium land holders in Pilibhit (U.P.) grow more trees (Eucalyptus, Poplar, Teak and Kadam) on their lands as compared to other categories. It is

Table 1 Potential C storage of Agroforestry systems in different eco-regions of the world

Country	Eco-region	System	Mg C ha^{-1}
Africa	Humid tropic high	Agri-silvicultural	29-53
South America	Humid tropic low	Agri-silvicultural	39-102[a]
	Dry low land		39-195
Southeast Asia	Humid tropical	Agri-silvicultural	12-228
	Dry lowlands		68-81
Australia	Humid tropics low	Silvi-pastoral	28-51
North America	Humid tropics high	Silvi-pastoral	133-154
	Humid tropics low		104-198
	Dry lowlands		90-175
Northern Asia	Humid tropical low	Silvi-pastoral	15-18

[a] Carbon storage value were standardize to 50 year rotation

estimated that total biomass production is likely to be 32,800 tonnes per year and stored carbon 16,400 tonnes per year (Singh, 2003).

Agrisilviculture

It is possible to design agri-silvicultural systems in which the organic matter loss under the crop component is matched by a gain under the tree component. Das and Itnal (1994) reported that organic carbon content was about double in agri-horticultural and agroforestry systems as compared to sole cropping (Table 2).

Alley cropping is a promising agroforestry technology for humid and sub-humid tropics in which food crops are grown between hedgerows of planted shrubs. The hedges (mostly legumes) are pruned periodically during the crop-growth and provide biomass which when added to soil acts as mulch and provides nutrients to soil. The lopping is also used as forage. After six years of *Leucaena leucocephala* based alley cropping, the organic carbon contents of the soil was 10.7 g kg^{-1} when pruning were retained as compared to 6.5 g kg^{-1} when these were removed (Kang *et al*., 1990). Similarly Lal (1989) found that over a period of six years (12 cropping seasons), the relative rates of decline in the status of nitrogen and organic carbon was much less under hedge-row-cropping of *Leucaena* and *Gliricidia* as compared to normal arable crops.

Table 2 SOC content after six years of plantation in different land use-systems

Land use system	Organic carbon (g kg^{-1})	
	0-15 cm	0-30 cm
Sole cropping	4.2	3.9
Agroforestry	7.1	7.2
Agri-horticulture	7.3	7.3
Agri-silviculture	3.8	4.7

In high rainfall coastal areas, particularly in Bay Islands and Kerala, most of the coconut growing area is inherently low in soil fertility. In addition, coconut holdings do not have the benefit of plant litter addition. In this context, soil improvement is one of the major attributes of coconut-based agroforestry systems, particularly on marginal lands. The beneficial interactions of mixed cropping and mixed farming components on soil fertility have been reported in Sri Lanka in terms of soil physical, chemical and biological properties (Table 3).

Table 3 Effect of mixed cropping on soil organic carbon and bulk density in 0-15 cm depth

	Cropping system	SOC (g kg^{-1})	Bulk density Mg m^{-3}	Earthworm population m^{-2}
A)	*Mixed cropping system*			
	Coconut only	8.6	1.56	28
	Coconut + Cocoa	14.2	1.26	214
	Coconut + Coffee	13.6	1.23	218
	Coconut + Pepper	12.7	1.27	191
	Coconut + Clove	12.0	1.19	204
	Coconut + Cinnamon	14.6	1.25	233
B)	** Mixed farming system*	16.3	1.24	-
C)	*Monoculture system*	9.6	1.56	-

Source: Liyanage & Dassanayake (1993). *Soil depth 0-30 cm.

Singh *et al*. (1989) studied the agroforestry systems involving *Populus deltoides* and *Eucalyptus hybrid* with aromatic grasses, *Cymbopogon martinii* and *C. flexuosus,* in the tarai tract of Kumaon hills. On an average, dry litter production of *P. deltoides* and Eucalyptus hybrid were 5 kg $tree^{-1}yr^{-1}$ and 1.5 kg $tree^{-1}yr^{-1}$, respectively. Under the canopies of these two trees, soil organic carbon was enhanced by 33.3 to 83.3 per cent and available nitrogen by 38.1 to 68.9% over control in 0-15 cm soil layer. Fertility build up under *P. deltoides* was significantly higher than *E. hybrid*. *Dalbergia sissoo* based agrisilviculture system at the age of 11 years was able to accumulate biomass 48.14 to 52.05 t $ha^{-1}$with carbon stock of 24.07 to 26.02 t ha^{-1} in semi arid regions of Jhansi, U.P., India. Carbon and nitrogen accumulation in herbaceous layer ranged from 0.28 to 0.56 t C ha^{-1} and 18.04 to 38.09 kg nitrogen ha^{-1}, respectively in different pruning regimes under blackgram-mustard crop sequence. Carbon and nitrogen content in tree and crop was slightly higher in greengram-wheat crop sequence (Ram Newaj *et al*., 2006). *Albizia*, mandarin and mixed crop accumulated 13.8 t ha^{-1} biomass (6.94 t C ha^{-1}) in Mamlay watershed in the south district of Sikkim (Sharma *et al*., 1995).

Silvipasture

Total carbon storage in trees + *Desmostachya* systems ranged from 6.80 to 18.55 t C ha^{-1} in root it was 1.48 to 3.66 t C ha^{-1} in the case of *Dalbergia sissoo* + *Sporobolous* *marginatus* and *Prosopis juliflora* + *Sporobolous marginatus* in sodic soils of northwestern India at 6 years (Kaur *et al*., 2002). *Acacia nolotica* could not survive along with *Sporobolous* under sodic conditions of the soil due the adverse effect of water logging and frost (Table 4).

Table 4 Carbon content in silvipastoral systems on a sodic soil in Kurukshetra, northwestern India

Silvipastoral system	Carbon content t C ha^{-1}	
	Trees (above and below ground biomass)	Grasses
Acacia nilotica + Desmostachya bipinnata	6.43	0.37
Acacia nilotica + Sporobolous marginatus	Mortality	1.18
Dalbergia sissoo + Desmostachya bipinnata	8.09	1.01
Dalbergia sissoo + Sporobolous marginatus	0.44	1.00
Prosopis juliflora + Desmostachya bipinnata	18.46	0.09
Prosopis juliflora + Sporobolous marginatus	12.08	0.24

Carbon mitigation potential was higher in silvipastoral (290.6 t ha^{-1}) when compared to agrihortisilviculture (312.4 t ha^{-1}) and natural grasslands (290.6 t ha^{-1}) in Solan (AICRPAF 2006). Silvipastoral system in degraded land in semiarid regions of Uttar Pradesh, India was able to accumulate 18.91 to 22.25 t ha^{-1} biomass in natural pasture and 32.20 to 35.01 t ha^{-1} biomass in established pasture (Table 5). The carbon storage in the system ranged from 1.89 to 3.45 t C ha^{-1} in silvipasture and 3.94 t C ha^{-1} in pure pasture (Rai *et al*., 2001). In another study, biomass production from natural pasture was 2.1 to 3.6 t ha^{-1} and from established/ improved pasture was 2.0 to 10.4 t ha^{-1}. It indicates that 1.8 to 3.5 times increase in biomass was due to adoption of silvipasture system in degraded lands (Rai, 1999).

Table 5 Biomass and carbon accumulation in silvipastoral system in degraded lands in semiarid regions of Uttar Pradesh, India

Silvipastoral system	Total biomass (pruned biomass of tree + grass biomass) in 5 years (t ha^{-1})	Average carbon content (t ha^{-1} $year^{-1}$)
Acacia nilotica (var. *Cupressiformis*)		
Natural pasture	18.91	1.89
Established pasture	32.20	3.23
Dalbergia sissoo		
Natural pasture	24.96	2.49
Established pasture	35.01	3.50
Hardwickia binata		
Natural pasture	22.25	3.25
Established pasture	34.56	3.45
Pure pasture	39.42	3.94

Conclusion

Climate change is the most sever problem that we are facing today in agriculture production and human health. Carbon sequestration through agroforestry is one of the biological mitigation options to slow down/soften the climate change. For increasing carbon pool through adding trees on the farm lands alone or in association with crops is one of the options to increase tree cover to the extent of 33%. Besides increase in the tree cover, restoration of degraded lands has a tremendous potential for carbon sequestration, improving soil quality and increasing productivity. Substitution of fossil fuel has greatest mitigating potential in long term and now a days production of bio-fuel and ethanol is the priority area to substitute the fossil fuel.

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Carbon Sequestration through Bamboo

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Introduction

Bamboo is a versatile and multifaceted non-timber plant and is the largest member of grass family. The gradual decreasing trend of wood timber which causes threat to human civilization can be minimized through bamboo as virtually every product which is now being produced from wood including panels, boards, flooring, roofing, pulp and paper, fabrics and cloth, charcoal, oil, gas, musical instruments, furniture can be effectively produced from bamboo. Owing to its versatile uses and wide adaptability, bamboo is considered as people's timber rather than poor men's timber and more than 1500 different products have been recorded so far with potentiality to increase further. Bamboo sector engages 432 million work days annually and thus bears high employment potential. More than 89 different species of bamboo are native to the North Eastern region of India and it is the integral part of the livelihood, economic, ecological, social as well as cultural identity of the region. In the last 15-20 years bamboo has emerged as a potential wood substitute. Development of bamboo resources and industries worldwide promotes economic and environmental growth, mitigates deforestation and illegal logging, prevents soil degradation and restores degraded lands. These qualities of bamboo have been well studied and are widely known.

Bamboo is an important part of many natural and agricultural eco-systems, providing a number of crucial ecosystem services. It provides food and raw materials for consumers in developing and developed countries. It regulates water flows, reduces water erosion on slopes and along riverbanks, can be used to treat wastewater and can act as windbreak in shelterbelts, offering protection against storms.

The wide distribution of bamboo across the tropics and subtropics of Asia, Africa and Latin America, with an annual production estimated between 15-20 million tonnes of fibre implies that it is highly significant as a livelihood material. Although traditionally associated more closely with Asian cultures, a number of economically important species are found in Latin America and Africa, where they too constitute important crops for local inhabitants. Dual characteristics of lightweight and high tensile strength of *Guadua angustifolia* have resulted in its main use as a building material throughout its range in Colombia, Ecuador and Peru. *Arundinaria alpine*, which is distributed in mountainous parts of East Africa, is an important source of construction material and fuel. Highest concentration of species occurs in South and Southeast Asia. Out of 1250 different bamboo species found globally 155 species are found in India and 89 species are native to North East, India. In NE, bamboo occupied a central role in the development of culture and civilisation with utilitarian, functional as well as spiritual significance.

Bamboo and development

Bamboo is relied on heavily by some of the world's poorest people, and can be a significant pathway out from poverty. It is commonly available as a common-pool resource and relatively easy to harvest and manage. Low investment costs for processing inputs and flexible time requirements for undertaking seasonal work means that bamboo-based employment is suitable to both full and part-time employment opportunities (INBAR, 2004). The development of the bamboo industry has led to job creation and raising rural incomes with associated benefits. For example, a conservative estimate indicates that there are 4.7 million people in India and 5.6 million people working in China's bamboo sector, 80% of whom are working in forest cultivation (Jiang, 2002). Case studies on 'bamboo counties' in Eastern China demonstrated the important role that the development of the bamboo sector can have in reducing rural poverty, maintaining high levels of rural employment. Impact assessments of INBAR in northern India shows that bamboo-based interventions have high value-addition through enhancing incomes, generating extra rural employment and empowering women in their communities. The expansion of global trade in bamboo is expected to contribute to development in bamboo growing areas. Currently bamboo contributes 4-7% to the total tropical and subtropical timber trade.

Bamboo and adaptation to climate change

Human beings are fundamentally dependent upon the flow of ecosystem services. Enhanced protection and sustainable management of natural resources and agricultural crops can play a critical role in climate change adaptation strategies (World Bank, 2010; TEEB, 2009). Bamboo is an important part of many natural and agricultural eco-systems, providing a number of crucial ecosystem services. It provides food and raw materials (provisioning services) for consumers in developing and developed countries. It regulates water flows, reduces water erosion on slopes, along riverbanks, can be used to treat wastewater, and can act as windbreak in shelterbelts, offering protection against storms. As poor people will be worse hit by the effects of climate change, action plans for adaptation need to be tailored to their situation (UNFCCC, 2007). Investing in 'ecological infrastructure' is increasingly acknowledged to be a cost-effective means of adapting to climate-change related risks, in many cases surpassing the use of built infrastructure (TEEB, 2009). For instance, the use of mangrove forests to protect shorelines provides an equal level of protection at a lower cost. Using bamboo forests as part of a comprehensive approach to rehabilitating degraded hillsides, catchment areas and riverbanks has shown promising and quick results (Fu and Banik, 1995). The light-weight and versatility of harvested bamboo also lends itself to innovations to cope with increased floods, such as raised housing in Ecuador and Peru and floating gardens in

Bangladesh. Bamboo thus has a high potential to be used in adaptation measures to alleviate threats imposed by local changes in climate on vulnerable populations.

Another major environmental service that humans rely on forests to provide is carbon sequestration, and a major part of forestry research is now focussed on quantifying how different forests perform as sinks (i.e. whether they absorb more carbon than they emit, and for how long) and as stores (how much carbon do they hold in their standing static state). Questions have similarly been raised over how well bamboo performs as a carbon sink. Although bamboo is a woody grass and not a tree, bamboo forests have comparable features and functions to other types of forests regarding their function in the carbon cycle. Bamboos have rapid growth rates, high annual re-growth after harvesting and high biomass production. Bamboo can easily compete with the most effective wood species in terms of carbon sequestration capacities. Bamboo has several advantages over tree species in terms of sustainability and carbon fixing capacity. Available studies conclude that bamboo biomass and carbon production may be 7-30% higher compared to the fast growing woody species. For instance, tropical *Bambusa bambos* produced total above ground biomass 287 t ha^{-1} with a mean annual production of around 47.8 t $ha^{-1}yr^{-1}$, almost twice that of the Eucalyptus clones. Interestingly, the total biomass of mature *Bambusa* at 6 years is higher than that of teak at 40 years, that is, 149 t C ha^{-1} as compared to only 126 t C ha^{-1} for teak. Sub-tropical moso bamboo (*Phyllostachys pubescens*) reaches above ground biomass of 137.9 t ha^{-1} and is generally harvested at 5-8 years intervals. Every 5 years it would produce at least 86 t ha^{-1} biomass and sequester 43 t C ha^{-1}, almost twice as much as a teak plantation under the same conditions. This includes total biomass as well as products.

Besides higher biomass, bamboo has other advantages over wood as a carbon stock. Unlike woody crops, bamboo offers the possibility of annual selective harvesting and removal of about 15-20% of the total stock without damaging the environment and stock productivity. Over 90% of bamboo carbon can be sequestered in durable products such as boards, panels, floors, furniture, buildings, cloth, paper and activated charcoal. These products have a very long life span and may retain carbon for several decades.

Bamboos are believed to perform roughly equivalent to fast growing plantation species with an increment biomass of between 5 and 12 t C ha^{-1} yr^{-1}. It is therefore hypothesised that bamboo has a capacity of carbon sequestration that is similar to that of fast growing forests. However, given the complexity of natural systems, and the fact that carbon cycle research in forests and especially in bamboo has started only recently, there are a number of issues which have been raised about factors which influence the performance of bamboo as a carbon sink.

The relationship between rates of bamboo growth and carbon sequestration

The growth of the new shoots in a bamboo forest occurs as a result of transfer of the energy accumulated in culms through photosynthesis in the previous year. As such, the growth of a bamboo culm is not driven by its own carbon sequestration, but by sequestration in previous seasons in other parts of the bamboo system, and as such growth of new shoots is not an indicator of sequestration rate. On the other hand, Zhou (2006) argues that as the bamboo system requires more inputs in the shooting season of young culms (when new shoots grow), high growth in bamboo shoots can be equated with a high rate of carbon sequestration. As long as carbon sequestration is determined by measuring the difference in standing carbon between year (t+1) and year (t) (a stock change approach), it doesn't matter whether and how the relocation of carbon between old and new culms occurs. Bamboo culms of most species reach maturity approximately in 7-10 years, after which they deteriorate rapidly, releasing carbon from the above-ground biomass back into the atmosphere (Liese, 2009). Therefore in a natural state, bamboo will reach a stable level of above ground carbon relatively quickly, where carbon accumulation through sequestration is offset by carbon release through deterioration of old culms. For the bamboo system to continue to be a net sink, carbon has to be stored in other forms, so that the total accumulation of carbon in a solid state exceeds the carbon released to the atmosphere.

Summary

The bamboo and trees have very different sequestration patterns, but are likely to have comparable carbon sequestration capacity, as long as the bamboo forest is managed and the total amount of harvested fibre is turned into durable products. The extensively managed bamboo forest ecosystems have a higher carbon stock (288.5 t C ha^{-1}) than intensive management systems (262-227 t C ha^{-1}). However, intensively managed plantations increase carbon stock in the arbour part of the bamboo (51-74 t C ha^{-1}) compared with extensively managed plantations (39-51 t C ha^{-1}). Therefore, intensively managed bamboo forests appeared to store about 1.4 times more carbon in the tree layer than extensively managed forests, while the carbon stock in the litter layer and soil of extensively managed bamboo forests appeared to be higher than those of intensively managed bamboo forests. Similarly, the annual fixed-carbon stock of Moso bamboo was reported at 12.7 t C (ha^{-1} yr^{-1}) when intensively managed, which is about 1.6 times the capacity when extensively managed (8.1 t C $ha^{-1}yr^{-1}$), 3.6 times the rate of Chinese Fir plantations, and 2-4 times the rate of tropical rain forests and pine forests (Zhou, 2006). Intensive management increases the density of the bamboo stands. The annually fixed-carbon stock of Moso bamboo can be as high as 20.1 to 34.1 t C ha^{-1} yr^{-1}. For the carbon in the litter and shrub layer and in the soil, i.e., the rhizomes, the roots and other carbon present in the soil, the indications point in the other direction (i.e., intensive management decreases carbon sequestration in the below ground pool). Within the understory of extensively managed bamboo forests, the annual carbon sequestration capacity can reach up to 0.546 t C ha^{-1}, and the litter layer up to 6.114 t C ha^{-1}, which is equal to roughly 2 times the capacity of intensively managed bamboo forests (3.049 t C ha^{-1}). Also, under intensive management, the soil total organic carbon (TOC), water-soluble organic carbon (WSOC), microbial biomass carbon (MBC) and mineralizable carbon (MC) were found to be significantly lower (Zhou, 2006). The repeated use of annual chemical fertilizers (itself a source of GHG) led to the decrease in water soluble carbon and soil microbial biomass carbon storage, causing a reduction in soil carbon storage (Jiang 2002; Zhou, 2006). Five years after intensive management, the TOC, WSOC, MBC and MC were significantly lower than those in extensively managed bamboo, and the TOC continued to decline for 20 years before stabilizing. It is clear that intensive management has mixed effects on the carbon sequestration capacity of bamboo stands, and that much more research is needed to establish the best management option for carbon sequestration.

Conclusions

Sustainable management and harvesting practices are essential for bamboo plantation and natural bamboo forest to exploit and sustain their capacity for carbon sequestration; if not properly managed or left unmanaged, the quantity of carbon sequestration in bamboo may be only about 30% in 30 years in sub-tropical region. Thus, to achieve higher level of carbon sequestration, sustainable bamboo management, regular harvesting and utilization for durable products should be advocated. Over 90% of bamboo carbon can be sequestered in durable products such as boards, panels, floor, furniture, building, cloth papers and activated charcoals. These products have a very long life span and can retain carbon for several decades leading to the much needed carbon sequestration process in the present context.

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Climate Change and Agriculture: Impact, Mitigation and Adaptation

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Introduction

Climate change is no longer a distant scientific prognosis; rather, it is becoming a reality which has already started to make its impact felt on every sphere of life on this planet. The climate has been changing naturally at its own pace since the beginning of time, but recently it has gained momentum due to anthropogenic interventions. The most imminent climatic change factor in recent times is the increase in the atmospheric temperatures due to increased levels of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluoro carbons (CFCs). The CO_2, CH_4 and N_2O concentrations in atmosphere were 280 ppm, 715 ppb and 270 ppb in 1750 AD (pre-industrial era) which have now risen up to 381 ppm, 1774 ppb and 319 ppb, respectively (IPCC, 2007a). These increases in GHGs have resulted in warming of the climate system by 0.74°C between 1906 and 2005. Eleven of the twelve years spanning from 1995 to 2006 rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The rate of warming has been much higher in recent decades. This has, in turn, resulted in increased average temperature of the global ocean, sea level rise, decline in glaciers and snow cover. There is also a global trend for increased frequency of droughts, as well as heavy precipitation events over most land areas. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent.

Currently, atmospheric concentrations of CO_2, CH_4 and N_2O, which account for about 60%, 15% and 5% of global warming, are rising at the rate of around 0.5% (2 ppm per year), 1% and 0.22% per year respectively. The Intergovernmental Panel on Climate Change (IPCC) Scenario indicates that CO_2 concentrations will be at least 550 ppm by 2050, between 605 and 755ppm by 2070 and likely to be doubled by the end of the century. IPCC has further projected that temperature increase by the end of this century is likely to be in the range 2 to 4.5°C with the best estimate of about 3°C, and is very unlikely to be less than 1.5°C (Fig1a&b).

It is also likely that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation. Himalayan glaciers and snow cover are projected to contract. The projected sea level rise by the end of this century is likely to be 0.18 to 0.59 m. It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions, continuing observed patterns in recent trends.

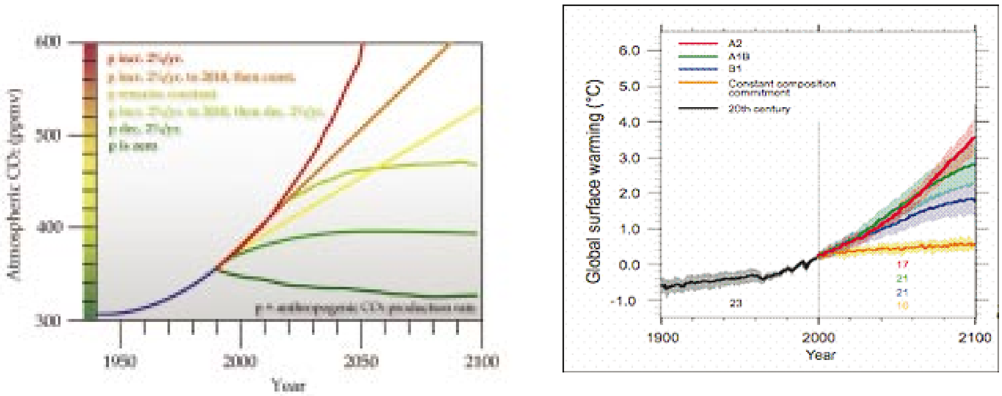

Fig 1 Projected rise in atmospheric CO_2 (a) and surface temperature (b) by different models (IPCC, 2007a)

Such global climatic changes will affect agriculture through direct and indirect effects on crops, soils, livestock and pests. Increase in atmospheric CO_2 has a fertilization effect on crops with C_3 photosynthetic pathway and thus promotes their growth and productivity. Increase in temperature, depending upon the current ambient temperature, on the other hand, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distributions of pest populations thus developing new equilibrium between crops and pests, hasten nutrient mineralization in soils, decrease fertilizer use efficiencies, and increase evapotranspiration. Indirectly, there may be considerable effects on land use due to snowmelt, availability of irrigation, frequency and intensity of inter- and intra-seasonal droughts and floods, and availability of energy. All of these can have a tremendous impact on agricultural production and hence food security of any region.

According to the Intergovernmental Panel on Climate Change (IPCC), in order to avoid any major catastrophic impact of climate change on agriculture, atmospheric concentrations of CO_2 must be stabilized at around 450 ppm and rise in global temperature must be contained within 2^0C over that of pre-industrial era. Since the CO_2 concentration has by now reached 390 ppm and the global temperature has already recorded a rise of around 1^0C over pre-industrial era, the world is left with the flexibility of emitting 60 ppm more CO_2 and pushing up 1^0C of temperature within which the high carbon lifestyle of developed countries like USA, Canada and Australia, the ambitious developmental needs of fast growing economy like India, China and Brazil, and the future growth prospects of underdeveloped countries in sub-Saharan Africa have to be accommodated which seems very unlikely. On top of these all, recurrent failures of world community to reach any legally binding agreement for curbing carbon emission lend further credibility to the projections of IPCC and ensure that these disastrous climatic projections do not stand wrong in future, signalling the world to be ready to face the catastrophic impacts of climate change on agriculture and hence food security.

Linkage between CO_2 and agriculture: past, present and future

Archaeological evidence indicates that a climatic factor not often considered, the CO_2 content, has throughout history had a great influence on agriculture; so much so that, it has been credited as the most important factor for the origin of agriculture at the beginning of Holocene. Agriculture originated independently in many distinct regions of the world at approximately the same time in human history. Humans in the Middle East domesticated lentils, barley, chick peas and wheat around 10,000 years ago. Rice, millets and the *Brassica spp.* were domesticated in the Far East 9,000 years ago. Beans and chili peppers were grown in Meso America 8,000 years ago. This synchrony in agricultural origins across the globe indicates that a common factor may have controlled the timing of the transition from foraging to food-producing societies.

According to Sage (1995), a global factor common to these widely diverse people was rise in atmospheric CO_2 from below 200 to near 270 ppm that occurred between 15 and 12 thousand years ago. Atmospheric CO_2 directly affects photosynthesis and plant productivity, with the largest proportional responses occurring below the current level of 390 ppm. In the late Pleistocene, CO_2 levels near 200 ppm were too low to support the level of productivity required for successful establishment of agriculture. Recent studies demonstrate that atmospheric CO_2 increase from 200 to 270 ppm stimulates photosynthesis and biomass productivity of C_3 plants by 25% to 50%, and greatly increases the performance of C_3 plants relative to weedy C_4 competitors. Rising CO_2 stimulates biological nitrogen fixation and enhances the capacity of plants to obtain limiting resources such as water and mineral nutrients. It also increases the ability of plants to remain productive during environmental stresses such as heat and drought. These results indicate that increases in productivity and reliability of food plants after 12000 years ago may have been substantial enough for plant husbandry to become a dependable mode of subsistence. CO_2 enrichment alone is unlikely to have caused the origin of agriculture; however, it could have removed a productivity barrier that inhibited plant cultivation, thereby allowing other causative agents to become important.

The 100 ppm rise in CO_2 from 270 to the present level during the last 120 years has coincided with another explosion in crop yields. The very successful plant breeding, irrigation, fertilization and better pest control would not have been as effective if the major plant nutrient, i.e., carbon had not been increasing during this time.

Life on earth is dependent directly or indirectly on photosynthetic activities of the plants. Carbon dioxide, the first molecular link between atmosphere and biosphere, is the primary raw material for photosynthesis and thus become the nerve of the entire food chain.

Plants with the C_4 photosynthetic pathway such as maize, sorghum, sugarcane etc. do not respond to elevated CO_2 because they have a biochemical CO_2 concentrating mechanism within the leaf. Consequently CO_2 fixation rate and growth are unaffected by increase in the atmospheric CO_2 concentration. In contrast, photosynthesis in C_3 plants like rice and wheat is affected by both short- and long- term changes in atmospheric CO_2 concentration because they do not have any CO_2 concentrating mechanism. In C_3 plants carbon assimilation increases with a rise in CO_2 concentration: first, because the current level of atmospheric CO_2 (which is close to the K_m 'Michaelis-Menton constant, defined as the substrate concentration at which the rate of an enzymatic reaction is half of its maximum' of the enzyme for carbon fixation 'Rubisco' to which CO_2 acts as a substrate), is sub-optimal to cause saturation in photosynthesis, any further increase in CO_2 concentration will increase the rate of photosynthesis; and second, because 'Rubisco' has an affinity for O_2 as well as CO_2, and at ambient CO_2 concentrations competition between the photoreductive carbon cycle and photorespiration reduces net CO_2 assimilation rates by 30-50%, higher CO_2 concentration increase the ratio of CO_2 to O_2 at the site of fixation, thereby increasing the rate of CO_2 fixation and growth (Long *et al.,* 2004).

The increased rate of photosynthesis and reduced carbon loss by photorespiration under elevated CO_2 is expected to increase the biomass yield of the agriculturally important C_3 crops like wheat, rice, soybean etc. However, associated rise in temperature will hastens the ontogenetic development of the plants substantially reducing the crop duration. As the crops will get lesser time for biomass accumulation and grain filling, rise in temperature is expected to offset the beneficial carbon fertilization effects of elevated CO_2 on crop plants. Irrespective of the theoretical benefits of CO_2 on agriculture and bio-resources, the secondary influences of rising temperature such as extreme weather variability, changed precipitation pattern, reduced water availability, deterioration in soil health and nutrient dynamics, altered photosynthate partitioning to economic plant parts, effects on survival and distribution of pest population etc. will frequently be counterproductive. The way these secondary influences will interact among themselves and the extent to which they negate the positive direct influences of CO_2 fertilisation is not at all clear which underlines the necessity of extensive research to be undertaken to establish which influence dominates yield outcomes and to further quantify the overall impact of climate change on agriculture.

Impacts on crop productivity and food production

Climate is a primary determinant of agricultural productivity. Rise in atmospheric carbon dioxide content, temperature and associated incidence of extreme weather events are the main climate change related drivers which impact crop productivity and food production across the globe. Although increase in CO_2 is likely to be beneficial to several crops such as rice, wheat and pulses, associated increase in temperatures, and increased variability of rainfall would considerably impact food production. According to the projections of IPCC (2007a), World agriculture will have to face a serious decline within this century due to global warming unless emissions of carbon dioxide and other greenhouse gases are substantially reduced from their rising path, and developing countries will suffer much steeper declines than the high income countries.

Developing countries in the tropics and sub-tropics of the world where average temperatures are already near or above crop tolerance levels are predicted to suffer an average 10 to 25 percent decline in agricultural productivity by the 2080s assuming a so called "business as usual" scenario in which greenhouse gas emissions continue to increase. Individual developing countries face even larger declines. India, for example, could see a drop of 30 to 40 percent. Some smaller countries in Africa suffer what could only be described as an agricultural productivity collapse. Sudan, already wracked by civil war fuelled in part by failing rains, is projected to suffer as much as 56 percent reduction in agricultural productivity potential; Senegal, a 52 percent fall.

Some of the developed countries situated in the temperate and near the Polar Regions of the world where the present temperature regimes are sub-optimal or not suited to agriculture could be benefitted by rising carbon dioxide as some additional land area is brought under cultivation by associated rise in surface temperature. IPCC (2007b) has projected that crop productivity is likely to increase slightly in temperate environments (e.g. in Northern Europe and North America) for local mean temperature increases of upto 1-3°C depending on the crop. This may decrease with further increase in temperature in some regions. China, further from equator than most developing countries, could escape major damage on average, although its south central region would be in jeopardy. The picture is similar in the United States, with projected reduction of 25 to 35 percent in the southeast and the south-western plains but significant increases in the northern states (Cline, 2007).

Table1 Summary of the estimates for impact of global warming on world agricultural productivity potential by 2080s (percent)

	Without carbon fertilization	With carbonfertilization
World	-16	-3
Rich countries	-6	8
Developing countries	-21	-9
Median	-26	-15
Africa	-28	-17
Asia	-19	-7
Middle East-North Africa	-21	-9
Latin America	-24	-13

Based on Cline William, *Global Warming and Agriculture: Impact Estimates by Country*

Some analysts have suggested that a small amount of global warming could actually increase global agricultural productivity. There might be some initial overall benefit to warming for a decade or two but - because future warming depends on greenhouse gas emission today- if timely and adequate action is not taken immediately with a sense of emergency, it would put global agriculture on an inexorable trajectory to serious damage.

IPCC (2007b) and a few other global studies indicate considerable probability of loss in crop production in India with increases in temperature. Some of these projected loss estimates for the period 2080-2100 are 5 to 30% (Rosenzweig and Parry, 1994; Fischer *et al.,* 2002; Parry *et al.,* 2004; IPCC, 2007b). These long-time estimates generally assume business as usual scenario, and a limited or nil adaptation by all stakeholders. A few Indian studies available on this theme also confirm similar trend of agricultural decline with climate change (Aggarwal and Sinha, 1993; Rao and Sinha, 1994; Saseendran *et al*., 2000; Aggarwal and Mall, 2002; Mall and Aggarwal, 2002).

There have been growing studies on the impact of climate change in India as well. As rice and wheat are the two most important cereals in the Indo-Gangetic Plains and are largely responsible for the food security of the country, most of the climate change related studies in India have focused on these two main crops. The recent trend of a decline or stagnation in the productivity of the rice-wheat cropping system in the Indo-Gangetic plain and north-western India has raised concerns. The wheat crop is sensitive to increases in the maximum temperature and rice is sensitive to increases in the minimum temperature in the tropical conditions of India. Although productivity declines may be partially offset by elevated CO_2 levels, possible water shortages and thermal stress would adversely affect the yield levels. Several crop growth simulation models show varying results of the impact on yields for wheat and rice in specific regions assuming specified higher temperature and CO_2 conditions.

Sinha and Swaminathan (1991) estimated that a 2^{o}C increase in the mean temperature could decrease the rice yield by 0.75 tons/ha in high yielding areas, and 0.06 tons/ha in the low yield coastal region. A 0.5^{o}C increase in the winter temperature could reduce wheat crop growth duration by 7 days and yield by 0.45 tons/hectare. A study by the Indian Agriculture Research Institute indicates irrigated wheat and rice yields will not be significantly affected due to the direct impact of the temperature increase and CO_2 concentration until 2050, but will show a large reduction in 2070 when the temperature increase is significant. Aggarwal *et al*., (2000) have shown that in northern India rice yields during last three decades are showing a declining trend and this is possibly related to increasing temperatures. Climate change is also projected to affect the agriculture and food production in northeast India. A detailed account of climatic changes and their likely impact on agriculture in this region can be found elsewhere (Manoj-Kumar, 2011a, b&c).

More recent studies done at the Indian Agricultural Research Institute indicate the possibility of loss of 4-5 million tons in wheat production with every rise of 1^{o}C temperature throughout the growing period even after considering benefits of carbon fertilization (Fig 2). This analysis assumes that irrigation would remain available in future at today's levels and there is no adaptation.

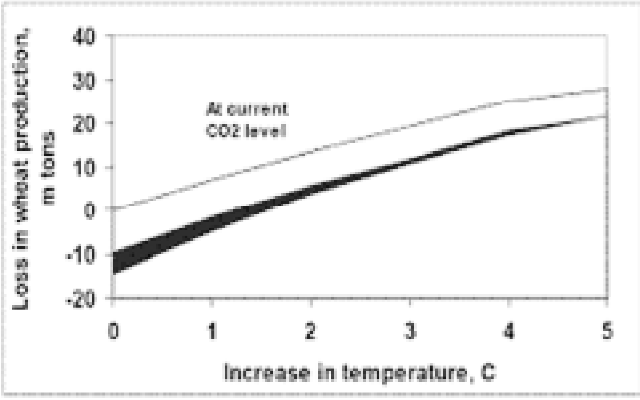

Fig 2 Projected loss in wheat production due to increasing temperature at current and 550 ppm CO_2 levels. The shaded areas of the curve indicate losses that can be offset by adaptation options such as change in planting dates and variety (Source: Aggarwal, 2007)

Keeping in view the current trend of rapidly declining groundwater table in wheat growing region of Indo-Gangetic plains, and future projections of erratic rainfall pattern, the assumption of irrigation availability in future at today's levels does not seem much convincing; further, as the wheat is currently grown mostly in irrigated areas and the irrigation availability at the critical growth stages of the crop is very crucial, actual loss of wheat production with rising temperature could be more severe than estimated by this study.

It is, however, possible for farmers and other stakeholders to adapt to a limited extent and reduce the losses (subsequent section discusses possible adaptation options). Simple adaptations such as change in planting dates and crop varieties could help in reducing impacts of climate change to some extent. For example, the study carried out at the Indian Agricultural Research Institute indicates that losses in wheat production at 1^{o}C increase in temperature can be reduced from 4-5 million tons to 1-2 million tons if a large percentage of farmers could change to timely planting and changed to better adapted varieties (Fig. 2). These adaptation benefits become smaller as temperature increases further.

The effect of rising temperature on grain yield of some winter crops namely wheat and barley- both cereals, mustard- an oilseed crop and gram- a pulse crop, in northern India was evaluated on the basis of historic datasets on meteorological sub-divisional scales, and through a dynamic crop growth model WTGROWS by Kalra *et al.,* (2008) (Fig.3). The reduction factors per degree rise in temperature, on average, were 4.26, 2.77, 0.32 and 1.32 q/ha for wheat, barley, gram and mustard respectively.

Studies indicate that the direct impact of rising temperature could be smaller on the kharif (early winter harvested) crop, but the crop will be highly vulnerable due to increased incidence of extreme weather (rainfall duration/intensity, drought/flood), pest and diseases,

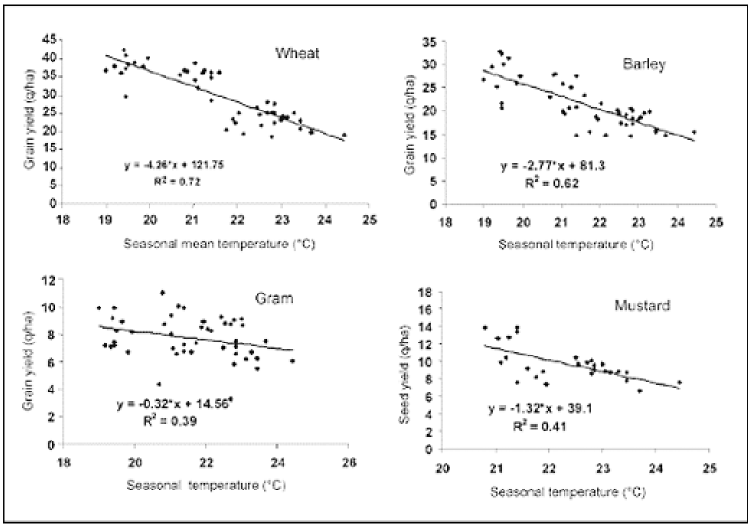

Fig 3 Effect of increase in seasonal temperature on yield (q/ha) of various *rabi* (winter) season crops (Source: Kalra *et al*., 2008)

and virulence. The Rabi crops (spring harvested) will be comparatively more vulnerable due to higher variation in temperature and uncertainties of rainfall and irrigation water availability. However, disappearance of the Himalayan glaciers and consequent drying up of the currently perennial rivers in the north and east may dry up the irrigation water supply to the rabi crop. In the long run, Indian agriculture may be seriously affected depending on the season, region and adaptation.

Impacts on nutritional quality of food

Although plants become healthier with every single molecule of carbon dioxide- a favourite food for them- pumped into the atmosphere, but then, the food which plant produces for human being is nutritionally not so healthy and could trigger a pandemic of human malnutrition in future high CO_2 world. In a meta-analysis of the available literature on effect of CO_2 on protein content of several food grains, Taub *et al*., (2008), reported decline in the protein concentrations in the grains of several food crops under elevated atmospheric CO_2. Wheat, rice and potato provide 21%, 14% and 2%, respectively, of protein in the human diet (FAOSTAT, 2007), and therefore, any decline in protein concentrations of these crops would have a devastating impact on human nutrition world over. As the nitrogen concentration in different crops has been widely reported to decline almost invariably when grown under elevated CO_2, it is bound to decrease the protein concentration in the food grains because nitrogen constitutes 16% of the grain proteins. At elevated CO_2 and standard fertilizer levels, wheat produces 10 to 13 % less grain protein (Fangmeier *et al*., 1999, Kimball *et al*., 2001, Manoj-Kumar and Patra, 2010, Manoj-Kumar *et al*., 2012a). Similarly, grain protein in rice (terao *et al*., 2005) and tuber nitrogen in potato Fangmeier *et al*., 2002) is reduced by about 10% at elevated CO_2 concentrations.

In a study of impact of increased temperature on quality of rice and wheat grains (Nagarajan *et al*., 2009), amylose content of rice grains which is an important determinant of cooking qualities decreased linearly with increase in mean temperature. This decline varied from 0.65% per degree rise in temperature in IR 64 rice to 0.30% in super basmati rice. High temperature also affected grain elongation and aroma in basmati rice. Protein content in wheat increased with increasing temperature (0.3% and 0.15% per ^{0}C respectively in bread wheat and durum wheat) due to increase in soluble (gliadin) protein as high temperature increases gliadin: glutenin ratio. However, according to IPCC (2001) the protein content of grain would decrease under both temperature and CO_2 increases. Since the rise in carbon dioxide and temperature affects protein content in mutually opposite direction as suggested by majority of the studies, the overall impact of these two factors, which will be more closer to reality, will depend on their interaction which has not been studied adequately, and calls for further research to reach a convincing conclusion.

According to an analysis by Loladze (2002), crops that grow in high CO_2 are nutritionally barren, denuded of vital micronutrients such as iron, zinc, selenium and chromium. If this is the case, nutritional well-being of human being will be in jeopardy, but the impact will hit some people harder than others. Most of the developing countries are already burdened by "hidden hunger"- chronic mineral and vitamin deficiencies caused by eating green revolution crops bred in 1960s and 70s. These high- yield crops staved off starvation, but turned out to be low in essential nutrients, particularly iron, zinc and vitamin A. Now those people will face a second dietary whammy, while millions more will be pushed over the edge into malnutrition. Loladze (2002) reported 17% and 28% decline respectively in iron and zinc content of rice (the world's most important crop) grown under elevated CO_2. Similar kind of discomforting trend of micronutrient reduction has been reported in wheat (the world's second most important cereal crop) and potato (most important vegetable crop) as well.

There are two mechanisms that potentially explain as to why does rising CO_2 concentration strip plants of some essential macro- and micronutrients. The first is a "biomass dilution" effect. As plants absorb more airborne carbon, they produce higher-than-normal levels of carbohydrates but are unable to boost their relative intake of soil nutrients. The result of this dilution effect is increased yields of carbohydrate-rich fruits, vegetables, and grains that contain lower levels of macro- and micronutrients.

To make matters worse, there is another effect dragging element ratios down. Excess CO_2 stifles a plant's ability to absorb these nutrients in the first place. Normally, plants absorb chemicals through their roots in two ways. Nutrients can be sucked in along with the water absorbed by the plant, or they can just diffuse into the root down a concentration gradient. Increased CO_2 disrupts both the mechanisms. Higher levels of CO_2 put a squeeze on the rate at which plants absorb water - by making them "breathe" less deeply. Normally, gases diffuse into plants through tiny stomatal pores in their leaves. But these open pores mean the plant loses water by evaporation. When the air contains more CO_2, plants can get away with narrowing the pores a little. That way, they get enough CO_2 while reducing their risk of drying out. But this has a profound effect on the water flowing through their tissues. If carbon-dioxide levels are doubled, transpiration decreases by about 23 percent. Roots suck in water using the pull of water evaporating through leaf pores. Reduced transpirational pull, even a little, under elevated CO_2 slows down the flow of water from the roots upward. With less water flowing through their system, plants suck in less of the micronutrients. And it gets worse - reduced water flow makes the soil wetter, which dilutes its nutrient content so diffusion rates drop. Overall, the effect drastically reduces the availability of nutrients in root zone subsequently reducing the concentration of macro- and micronutrients in edible plant parts. Apart from reduction in micronutrients' concentration (particularly Zn and Fe), their bioavailability is also expected to decline under the elevated CO_2 atmosphere (Manoj-Kumar, 2011d)

Put simply, a mouthful of rice, has a lower concentration of micronutrients today than it did just a few generations ago, and a bite of bread in the CO_2-enriched atmosphere of the future will end up being less nutritious than the one in our current CO_2 atmosphere. Keeping in view the fact that over half of the world's population (~3.5 billion people) is already suffering from iron- and zinc deficiency induced health problems, any further decline in the concentration of these micronutrients will severely impact the nutritional security of human being in the high carbon dioxide world of future.

Impacts on soil health and its suitability for agricultural production

Soil is nature's most precious gift to the mankind. The economic viability and environmental amenity of agricultural sector depends heavily on 'soil health'. Of the range of potential indicators used to infer soil health status, soil carbon is particularly important. Organic matter is vital because it supports many soil processes that are associated with fertility and physical stability of soil across the various ecosystem services. In particular organic matter provides an energy source for microbes, structurally stabilizes soil particles, stores and supplies plant essential nutrients such as nitrogen, phosphorus and sulphur and provides cation/anion exchange for retention of ions and nutrients. Carbon within the terrestrial biosphere can also behave as either a source or sink for atmospheric CO_2 depending on land management, thus potentially mitigating or accelerating the greenhouse effect. Cycling of soil organic carbon is strongly influenced by moisture and temperature, two factors which are predicted to change under global warming. Overall, climate change will shift the equilibrium, both directly and indirectly of numerous soil processes. These include carbon and nitrogen cycling, nutrient dynamics, acidification, risk of erosion, salinisation, all of which will impact on soil health. The link between climate change and soil health impact is schematically presented in figure 4.

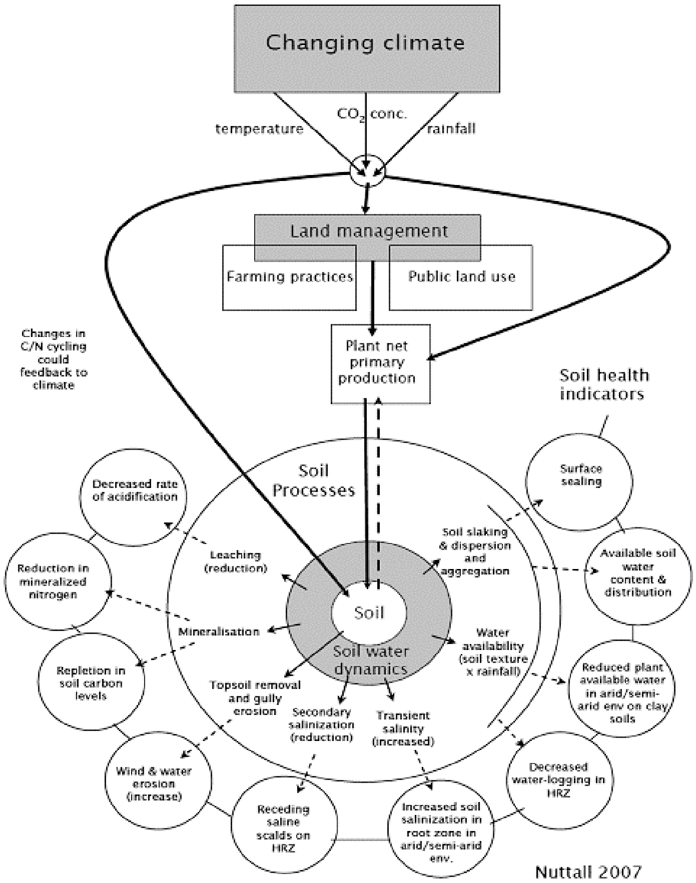

Fig 4 Potential links between climate change and soil health (Source: Nuttal, 2007)

Soil organic carbon and nutrient dynamics

Worldwide, Soil carbon levels are expected to decrease due to decreased net primary production as an effect of climate change. Any gains by increased plant water use efficiency, due to elevated CO_2 are likely to be outweighed by increased carbon mineralization after episodic rainfall and reduced annual and growing season rainfall. The quality of soil organic matter may also shift where the more inert components of the carbon pool prevail. The residues of crops under elevated CO_2 will have higher C:N ratio (Manoj-Kumar *et al*., 2007; Manoj-Kumar and Bhadraray, 2009, Manoj-Kumar, 2010), and this may reduce their rate of decomposition and nutrient supply. In contrast, increase of soil temperature is expected to increase nitrogen mineralization, but then increased gaseous losses of nitrogen through processes such as volatilization and denitrification may reduce its overall availability to plants. Increased microbial population in crop rhizosphere under elevated CO_2 may also compete with the crop plants for available nutrients in the soil. Soil biology and microbial populations are expected to change under conditions of elevated CO_2 and changed moisture and temperature regimes. As soil biology regulates nutrient dynamics and many disease risks, nutrient availability to crops could change as could the exposure to soil-borne diseases.

Soil salinisation

Transient salinity may increase in soil under future climate change. Transient salinity increases as capillary rise dominates at higher temperature, bringing salts into the root zone in salt affected soils. Leaching during episodic rainfall events may be limited due to surface sealing. Increased subsoil drying increases concentration of salts in the soil solution. Conversely, the severity of saline scalds due to secondary salinisation may abate, as groundwater levels fall in line with reduced rainfall. Rise in sea level also may lead to salt-water ingression in the coastal lands turning them less suitable for conventional agriculture.

Soil erosion and nutrient loss

An increased risk of soil erosion and nutrient loss due to reduced vegetation cover in combination with episodic rainfall and greater wind intensities is expected. Runoff and soil loss by erosion are most vulnerable to changing rainfall pattern under future scenario of climate change. In order to assess the impact of climate change on soil erosion and runoff, Tripathi *et al*. (2009) selected seven watersheds in different agro-climatic regions across the country and used AVSWAT model to estimate the projected runoff and soil loss between 1961-1990 and 2071-2100. The frequency of occurrence of annual runoff of the magnitude of over 300 mm was projected to increase by 26.1% in Umiam (Meghalaya) to 200% in Antisar (Gujarat) thus increasing the frequency of flood. The frequency of annual runoff of less than 50 mm was expected to vary between 10% in Pogalure (Tamil Nadu) and 100% in Jonainala (Orissa) thus increasing the frequency of drought. During the same period, soil loss is likely to increase by 3.7% in Udhagamandalam (Tamil Nadu) to about 757% at Pogalur (Tamil Nadu), with around 71% increase at Umiam (Meghalaya). These huge amounts of soil loss by erosion can potentially strip the top soil of their organic matter and nutrient content, thus rendering the soil unfit for crop cultivation in future.

Impacts on insect pests and diseases

Crop-pest interactions will change significantly with climate change leading to impact on pest distribution and crop losses. Crop-weed competition will be affected by rising atmospheric CO_2 depending upon their photosynthetic pathway. C_3 crop growth would be favoured over C_4 weeds affecting the need for weed control. However, the associated rise in temperature may further alter the competition depending upon the threshold ambient temperatures. Diseases and insect populations are strongly dependent upon temperature and humidity. Any increase in these parameters, depending upon their base value, can significantly alter their population, which ultimately results in yield loss. Even with small changes, the virulence of different pests changes. For example, at 16ºC, the length of latent period is small for yellow rust. Once the temperature goes beyond 18ºC, this latent period increases, but that of yellow and stem rusts decreases (Nagarajan and Joshi, 1978). The appearance of black rust in north India in sixties and seventies was related to the temperature dependent movement of spores from south to north India (Nagarajan and Joshi, 1978).

Monocyclic diseases such as stem rot, sheath rot and false smut are less influenced by ambient weather conditions. Epidemics of monocyclic diseases are relatively rare in the sense of an explosive increase in their population. In contrast, polycyclic diseases such as blast, brown spot, bacterial leaf blight and rice tungro virus, which invade the aerial parts of the plants, are subjected to constant interaction with the weather, and are more likely to be affected by change in climate. They easily attain epidemic proportions to cause heavy losses (Abrol and Gadgil, 1999).

For every insect species there is a range of temperatures within which it remains active from egg to adult stage. Lower values of this range are called 'threshold of development' or 'developmental zero'. Within the favourable range, there is an optimum temperature at which most of the individuals of a species complete their development. Exposure to temperatures on either side of the range exerts an adverse impact on the insect by slowing down the speed of development. If ambient temperatures remain favourable for the pest after temperature increases, the pest incidence may be expected to rise due to increased rates of development, which may result in the completion of more pest generations. However, the pest population would be adversely affected once the ambient temperature exceeded the favourable range.

Studies have shown that insects remain active within a temperature range from 15º to 32ºC (Phadke and Ghai, 1994). In the case of red cotton bug at constant temperatures of 20, 25 and 30ºC, the average duration of life-cycle was found to be 61.3, 38.3 and 37.6 days respectively, while at 12.5 and 35ºC the pest did not show any development (Bhatia and Kaul, 1966). The most congenial temperatures for insect development have been suggested by Phadke and Ghai (1994). For the mustard aphid, *Lipaphis erysimi,* a maximum temperature ranging from 19–24ºC is suggested, with a mean of 12–15ºC; for rice stink bug, a maximum temperature between 26.9 and 28.2ºC with a relative humidity of 80.6–82.1%; for rice green leafhopper, a temperature from 20–28ºC ; for the brown plant hopper, a temperature from 24.8–28.6º; for aphids, thrips and leaf weevils, a mean temperature around 27.5–28.5ºC; and a maximum temperature from 23–27.8ºC is required for the gram pod borer.

Forecasting the appearance of aphids *(Lipaphis erysine* Kalt) on mustard crops grown during the winter season in the northern part of India based on the movement of western monsoon disturbances has been achieved (Ramana Rao *et al.*, 1994). Western disturbances bring in cold and humid air from the Mediterranean region, resulting in cloudy and favourable weather conditions for the occurrence of aphids on mustard crops. It was shown that there was a sharp increase in the population of aphids when the mean daily temperature ranged from 10º to 14ºC, with a relative humidity of 67–85% and cloudiness greater than 5 octas. The swarms of locust produced in the Middle East usually fly eastwards into Pakistan and India during the summer season and lay eggs during the monsoon period. The swarms resulting from this breeding return during autumn to the area of winter rainfall, flying to all parts of India and influencing kharif crops (Rao and Rao, 1996). Changes in rainfall, temperature and wind speed may influence the migratory behaviour of locusts.

Pests such as the armyworm, *Mythimna separate,* achieve higher population growth leading to outbreaks after heavy rains and floods. On the other hand, pests such as *Pyrilla perpusilla* become more damaging under drought conditions. Less frequent but intense rains in future will cause floods as well as droughts, which will thus influence the incidence of pests. Some pests, such as the cabbage white butterfly, *Pieris brassicae,* migrate to the plains in winter and back to the hills in summer. With milder winters in the hills and increasing temperatures, such migrations will also be affected. With shorter cold seasons, the onset of diapauses will be delayed in autumn, while its termination may be hastened in spring, thereby increasing the period of activity of pests.

Pest population dynamics simulation models can be used to simulate population dynamics and assess the impact of climate change on pest incidence. A dynamic simulation model was developed for the rice stink bug, *Leptocorisa acuta*, using a thermal time concept (Fig 5). It was found that up to a 2ºC rise in daily average temperature over 2001's weather would increase the pest population, while further increases in temperature would have an adverse effect on pest populations.

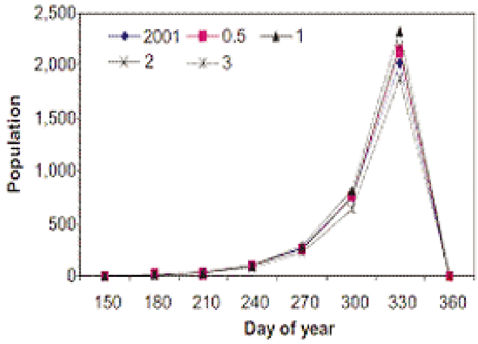

Fig 5 Simulation of the effect of temperature rise on the rice stink bug population (Source: Reji *et al*., 2003)

Impacts on livestock production and productivity

Livestock productivity is affected both directly and indirectly. Direct effects involve consequences for the balance between heat dissipation and heat production. According to Hahn (1995, 2000), a change in this balance can alter: a) animal mortality, b) feed conversion rates, c) rates of gain, d) milk production, and e) conception rates. Appetite may also be affected (Adams *et al*., 1998). Finally, carrying capacity in a region is altered by changes in the availability of feed and fodder.

Due to the paucity of long term data, there are very few studies on the impact of climate change on the livestock. Global warming could increase water, shelter and energy requirements for raising livestock. Heat stress can also adversely affect the reproductive performance and productivity of milk animals, and hence reduce the area where high yielding dairy cattle (cross-breeds) can be economically reared. Milk is an important component of food that is significantly increasing in demand. Increased heat stress associated with global climate change may, however, cause distress to dairy animals and possibly impact milk production.

Temperature-Humidity Index was used (Upadhyay *et al.,* 2009) to relate animal stress with productivity of milk of buffaloes, crossbred and local cows. These studies indicated that India losses 1.8 million tonnes of milk production at present due to climatic stresses in different parts of the country. Global warming will further negatively impact milk production by 1.6 million tonnes by 2020 and more than 15 million tonnes by 2050. High producing crossbred cows and buffaloes will be impacted more than indigenous cattle. Northern India is likely to experience greater impact of global warming on milk production of both cattle and buffaloes in future.

A rise of 2 to 6^{0}C due to global warming will negatively impact growth puberty and maturity of crossbreds and buffaloes. Time required for attaining puberty of crossbreds and buffaloes will increase by 1 to 2 weeks due to their higher sensitivity to temperature than indigenous cattle. It will negatively impact oestrous expression, duration and conception of buffaloes. Scorching heat waves and rising temperatures could lead to increased heat-related diseases like heat strokes in the livestock population. Reports also suggest an increasing incidence of ticks and insect borne diseases in India.

Climate change may also potentially impact the livestock agriculture indirectly. Extreme weather conditions like heavy rainfall/floods in some areas and coastal flooding due to a rise in sea water could result in contaminated water and sewerage services, which in turn could lead to the spread of a range of water and food borne diseases. Expected droughts in some areas could lead to increasing malnutrition due to starvation among animals. An increase in the incidences of natural disasters (tropical storms, hurricanes, cyclones and floods in some areas and droughts in others) and consequent frequent displacement of the livestock population in affected area(s) could result in higher mortality of animals.

Impacts on forestry and biodiversity

India is a country rich in biodiversity where forests account for about 20% (64 million ha) of the geographical area. With nearly 200,000 villages classified as forest villages, there is obviously a great dependence on forest resources by communities. One tenth of the world's known species of higher altitude animals and plants occur in the Himalayas. In 1995, approximately 10 percent of the known species in the Himalayas were listed as 'threatened'. Climate is an important determinant of the geographical distribution, composition and productivity of forests. Rabindranath and Sukumar (1998) estimated the impacts of two climate change scenarios on tropical forests in India- one involving greenhouse gas forcing and the other incorporating the effects of sulphate aerosols. The first scenario, associated with increased temperature and rainfall, could result in increased productivity, migration of forest types to higher elevations and transformation of drier forest types to moister types. The second scenario involving a more modest increase in temperature and a decrease in precipitation in central and northern India could have adverse effects on forests and biodiversity therein.

Global climate change is also likely to lead to a shift of the temperate ecosystem to higher elevations and increased erosion and overland flows in the steep terrains of the Himalayan range. Increased temperature and rainfall may lower the productivity of forest resources. One study predicts that due to a decline in soil moisture availability caused by warmer temperatures, productivity of teakwood, India's most preferred wood species, could decline from 5.4m3 per hectare to 5.07 m^3 per hectare, and a decline in productivity of deciduous forests may take place from 1.8m3 per hectare to 1.5 m^3 per hectare. High temperature and moisture stress, coupled with extreme weather conditions could lead to higher natural degradation of forests.

Impacts on coastal agriculture and fisheries

Densely populated and intensively cultivated low-lying coastal lands are vulnerable to coastal erosion and land loss, inundation, sea flooding and upstream movement of sea water into fresh water tributaries. India's 7,500 kilometres coastline will be particularly hard-hit by climate change. Large scale migration of people from coastal zones may occur due to submergence of coast lines after the rise in sea levels. Research shows that a one meter rise in the sea level will affect an area of 5,763 square kilometres and displace about 7.1 million people in India. Rice cultivation, commercial fishing and prawn farming practiced in coastal regions could be severely affected. Inundation of the coastal region and consequent problems of salinity in the adjoining tributaries may also adversely affect inland agriculture. Agriculture will be worst affected in the coastal regions of Gujarat and Maharashtra, where agriculturally fertile areas are vulnerable to inundation and salinisation.

Regional changes in the distribution and production of particular fish species are expected due to continued warming, with adverse effects projected for aquaculture and fisheries. Sea surface temperature in the Indian seas may increase by about 3˚C by 2100. Increasing sea and river water temperature is likely to affect fish breeding, migration and harvests. A rise in temperature as small as 1˚C could have important and rapid effects on the mortality of fish and their geographical distributions. Oil sardine fishery did not exist before 1976 in the northern latitude and along the east coast as the resource was not available, and sea surface temperatures were not congenial. With warming of sea surface, the oil sardine is able to find temperature to its preference especially in the northern latitudes and eastern longitudes, thereby extending the distributional boundaries and establishing fisheries in larger coastal areas. Corals in Indian Ocean will be soon exposed to summer temperatures that will exceed the thermal thresholds observed over the last 20 years. Annual bleaching of corals will become almost a certainty from 2050.

Impacts on cost of cultivation, farm profitability and environmental quality

Changes in climate are expected to affect the productivity and aggregate demand for inputs in agriculture such as water, labour, energy, equipments, fertilizer, and plant protection chemicals which will, in turn, increase the cost of cultivation and finally bring down farm profitability. Kumar and Parikh (1998) have showed that even with adaptation by farmers of their cropping patterns and inputs, the loss in farm-level net revenue is estimated to range between 9% and 25% for a temperature rise of 2^0C-3.5^0C. Increased incidences of pest infestation and disease outbreak in agricultural crops at higher temperature and humidity in future will increase the cost on plant protection chemicals. The rising levels of atmospheric CO_2 are likely to increase biomass production and yield of C_3 crops such as rice, wheat and soybean, but the absolute increase in productivity will occur only when nitrogen and phosphorus availability in soil is high (Manoj-Kumar *et al.,* 2011a,b&c, 2012a&b).

Manoj-Kumar *et al*., (2009b) studied the impact of low (120 kg N ha^{-1}), medium (180 kg N ha^{-1}) and high (240 kg N ha^{-1}) nitrogen applications on yield and quality of wheat grains in sub-tropical India under elevated atmospheric carbon dioxide (650 ppm) concentration. Although grain yield responded positively at all the three levels of nitrogen application but the response was maximum at higher doses. Relatively very small increase in yield at low N level was attributed to nitrogen deficiency faced by plants as indicated by appearance of N deficiency symptoms under elevated CO_2 concentration. Nitrogen concentration of wheat grains which is an important determinant of grain nutritional quality contributing 16% to the total grain protein, also decreased under elevated CO_2 at low level of N supply but medium and high doses of N caused an improvement in N content of wheat grains at high CO_2. The results underline the requirement of enhanced fertilizer-nitrogen application to wheat crop for sustaining higher productivity and maintaining nutritional quality of wheat under the futuristic ecosystem of elevated atmospheric carbon dioxide. However, the decrease in fertilizer-nitrogen use efficiency at the higher doses, which is required under elevated CO_2, is a matter of great concerns both economically as well as environmentally (Table 2).

Table 2 Fertilizer-N use efficiency in wheat as influenced by interaction of atmospheric CO_2 and levels of fertilizer-N application

Fertilizer N levels	Levels of atmospheric CO_2	
	Ambient	Elevated (650 ppm)
100%	25.24[ab]	27.49[a]
150%	19.46[cd]	22.33[b]
200%	12.74[c]	16.66[d]

As the atmospheric CO_2 concentration rises, phosphorus requirements for plants growing in managed ecosystems will also need reassessing. Since most of the C_3 crop species fail to respond to high CO_2 when phosphorus is low- possibly because insufficient phosphorus is available to maintain maximum photosynthetic activity at high CO_2, higher rates of P fertilizer are likely to be needed to sustain maximum productivity of a number of crop species in future (Conroy, 1992; Manoj-Kumar *et al*., 2012a,b&c) (Table3).

Table 3 Effect of phosphorus nutrition and CO_2 enrichment on wheat yield
(Source: Conroy, 1992)

Phosphorus	CO_2 (ppm)	No. of grainsper head	Weight of grains per head (g)
Low	340	13	0.5
	660	12	0.5
High	340	22	0.8
	660	33	1.3

Difference between a pair of values with any common letter as superscript is statistically non-significant ($p<0.05$). Values in percent (%) represent percent of the recommended dose (STCR recommendation) of fertilizer-N applied.

As nitrogen and phosphorus are the two most deficient nutrient elements in the soil world over, particularly in India, higher doses of these elements through external application of fertilizers will be required to sustain the higher productivity of plants under elevated CO_2. Fertilizer use efficiency in India is generally very low (30-50%). Increasing temperature in future is likely to further reduce fertilizer use efficiency. Higher frequency of heavy rainfall as projected in future will further aggravate the problem of nitrate pollution of ground water by facilitating more NO_3^{-1}leaching from the soil. As the fertilizer is most costly input in agriculture, and also its loss is associated with several environmental hazards (such as nitrate pollution of ground water, N_2O emission into atmosphere causing global warming and eutrophication of water bodies), application of higher doses of fertilizers with reduced use efficiency will increase the cost of cultivation as well as degrade the environmental quality in future scenarios of elevated CO_2 and temperature.

Irrigation is another very costly and critical input in crop production which will be required more frequently at higher temperature due to accelerated drying of soil through higher evapo-transpirational loss of water in future. Higher cost will also be incurred on proper management of livestock to protect it from heat stresses induced by global warming. Put simply, reduced productivity of crops and livestock, and increased cost of agro-inputs will have a discomforting impact on farming by pulling down the overall profitability in agriculture under projected scenario of climate change in future.

Agriculture and climate change mitigation

Mitigation is a response strategy to climate change, and can be defined as measures that reduce the amount of emissions (abatement) or enhance the absorption capacity of greenhouse gases (sequestration). Regardless of the projected or actual impacts of climate change, agriculture is also likely to be directly or indirectly involved in climate change mitigation efforts. Agriculture acts as both, source as well sink of greenhouse gases. CO_2, CH_4 and N_2O are important greenhouse gases contributing 60%, 15% and 5% respectively to global warming. The IPCC (2007a) estimates that globally agriculture emits about 20%, 50% and 70% of the total anthropogenic emissions of these gases. Agriculture sector contributes 28% of the total GHG emissions from India (NATCOM, 2004, Fig.6)

Carbon dioxide emissions arise from fossil fuel usage, soil tillage, deforestation, biomass burning and land degradation. Biological generation of methane in anaerobic environment including enteric fermentation in ruminants, flooded rice fields, and anaerobic animal waste processing, are the principal sources of CH_4 from agriculture. Nitrous oxide emissions come from manure, legumes and inefficient fertilizer use.

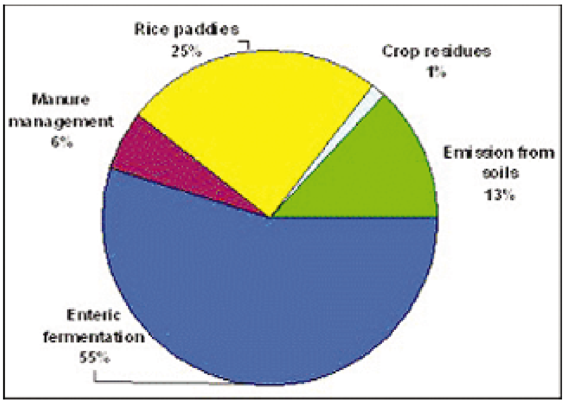

Fig 6 Relative contribution of different sectors in agriculture to GHG emissions
(Source: NATCOM, 2004)

There are several approaches that can assist in reducing GHG emissions from agriculture. Mitigation of CO_2 emission from agriculture can be achieved by increasing carbon sequestration- a process of transferring carbon dioxide from the atmosphere into soil and plant in a form that is not immediately reemitted. This transfer of carbon helps off-set emission from fossil fuel combustion and other carbon emitting activities while enhancing soil quality and long term agronomic productivity. Soil management practices such as reduced tillage, manuring, residue incorporation, improving soil biodiversity, micro aggregation and mulching can play important roles in sequestering carbon in soil. Forests and stable grass lands are referred to as potential carbon sinks because they can store large amounts of carbon in their vegetation and root systems for long periods of time. Therefore, afforestation on marginal and degraded land is another carbon sequestration strategy.

Methods to reduce methane emissions from enteric fermentation include enhancing the efficiency of digestion with improved feeding practices and dietary additives. Feed composition should be carefully altered, either to reduce the percentage which is converted into methane or to improve the milk and meat yield. The efficacy of these methods depends on the quality of feed, breed and age of livestock. Strategies to reduce methane emission from rice cultivation could be altering water management, particularly promoting mid-season aeration by short-term drainage; improving organic matter management by promoting aerobic degradation through composting or incorporating it into soil during off-season drained period; use of rice cultivars with few unproductive tillers, high root oxidative capacity and high harvest index; and application of fermented manure like biogas slurry in place of unfermented farm yard manure.

Site-specific nutrient management could be the most efficient management practice to reduce nitrous oxide emission from agricultural soil. Any measure which increases the use efficiency of applied nitrogenous fertilizer will reduce the N_2O emission from the soil. In a field experiment conducted at the farm of Indian Agricultural Research Institute, New Delhi, Pathak and co-workers studied the effectiveness of various nitrification inhibitors in mitigation of nitrous oxide and methane emission from rice–wheat system of Indo- Gangetic plain. They reported substantial reduction in N_2O-N emission on the application of nitrification inhibitors which ranged from 5% with hydroquinone to 31% with thiosulphate in rice and 7% with hydroquinone to 29% with DCD in wheat crop. Nitrification inhibitors also influenced the emission of CH_4. There are some plant-derived organics such as *neem* oil, *neem* cake and *karanja* seed extract which can also act as nitrification inhibitor.

Agriculture and climate change adaptation

Adaptation to climate change can be defined as an adjustment made to a human, ecological or physical system in response to a perceived vulnerability of various sectors of agriculture, aiming to reduce the overall adverse impact of changing climate on agriculture. Potential adaptation strategies to deal with the impact of climate change include developing cultivars tolerant to heat and salinity stress and resistant to flood and drought, modifying crop management practices, improving soil and water management, improving fertilizer use efficiency, adopting new farm techniques such as resource conservation technologies, crop diversification, improving pest management, conserving biodiversity, agronomic and genetic interventions to produce nutrient-rich (protein, iron and zinc) crops, better weather forecast and crop insurance, and harnessing the indigenous technical knowledge of the farmers.

Changes in land use- and crop management practices: Small changes in climatic parameters can often be managed reasonably well by altering dates of sowing, spacing and input management. Adjustment of planting dates to minimize the effect of temperature increase-induced spikelet sterility can be used to reduce yield instability, by avoiding the flowering period to coincide with the hottest period. Adaptation measures to reduce the negative effects of increased climatic variability, as normally experienced in arid and semi-arid tropics, may include changing the cropping calendar to take advantage of the wet period and to avoid extreme weather events during the growing season. Development of alternate cultivars and farming systems (such as mixed cropping, crop-livestock) that are more adaptable to changes in the environment can further ease the pressure.

Soil water management: A broad range of agricultural water management practices and technologies are available to spread and buffer production risks. Enhancing residual soil moisture through land conservation techniques assists significantly at the margin of dry periods while buffer strips, mulching and zero tillage help to mitigate soil erosion risk in areas where rainfall intensities increase. Water harvesting techniques and micro catchments are extremely beneficial in increasing biomass production in arid climates. Improvement in water use efficiency through measures such as advanced irrigation systems, viz. Drip irrigation technologies; centre-pivot irrigation systems, etc. coupled with reduction in operating hours, can significantly reduce the amount of water and nitrogen applied to the cropping system. This reduces emissions of nitrous oxide and water withdrawals.

***Adoption of resource conserving technologies*:** Resource- conserving technologies involving zero- or minimum tillage with direct seeding, permanent or semi-permanent residue cover, and crop rotations have potential to improve the use efficiency of natural resources, including water, air, fossil fuel and soil. Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yields to when planted under normal conventional tillage over a diverse set of soil conditions. In addition, such resource conserving technologies improve soil organic carbon status, and restrict the release of soil carbon thus mitigating increase of CO_2 in the atmosphere (Table 4).

Table 4 Effect of different tillage practices on soil organic carbon content (g kg^{-1}) after six years of soybean wheat cropping cycles in a Vertisol
(*Source:* Anonymous, 2007)

Soil depth (m)	Soil organic carbon content (g kg^{-1})			LSD *(P=0.05)*
	No tillage	Reduced tillage	Convention tillage	
0-0.05	13.08	12.47	11.01	1.23
0.05-0.15	8.01	8.70	7.20	0.92
0.15-0.30	6.69	6.42	5.57	1.04

***Development of climatic-stress resistant crop*:** most of the currently grown agricultural crops have not been developed to face the severity of the extreme climatic stress (such as temperature extremes, drought, flood, salinity, wind storms, nutrient deficiency in soil, frequent pest attack etc.) anticipated in future. Therefore, one important adaptive option includes developing climatic-stress resistant crop by intensive search for stress tolerance genes in wild genotypes, developing transgenic for biotic and abiotic stresses, transforming C_3 plants to C_4 photosynthetic pathway which is more efficient in utilizing atmospheric carbon dioxide.

***Improved risk management though early warning system and crop insurance*:** The increasing probability of floods and droughts and other uncertainties in climate may seriously increase the vulnerability of resource-poor farmers to global climate change. Early warning systems and contingency plans can provide support to regional and national administration, as well as to local bodies and farmers to adapt. Policies that encourage crop insurance can provide protection to the farmers in the event their farm production is reduced due to natural calamities.

Harnessing the indigenous technical knowledge of the farmers: For centuries, Farmers in South Asia, often poor and marginal, have been facing, and are experimenting with the climatic variability. Although there is a large body of knowledge within local communities on coping with climatic variability and extreme weather events, rapidly changing climate conditions will require upgrading local knowledge with more scientific observations and establishing collaboration among neighbours and neighbouring countries to transfer knowledge from areas already experiencing these changes.

***Conservation of Agro-biodiversity*:** Biodiversity in all its components (e.g. genes, species, ecosystems) increases resilience to changing environmental conditions and stresses. Genetically-diverse populations and species-rich ecosystems have greater potential to adapt to climate change. Therefore, promoting use of indigenous and locally-adapted plants and animals as well as the selection and multiplication of crop varieties and autochthonous races adapted or resistant to adverse conditions is also an effective strategy for adaptation to climate change.

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Climate Change and Crop Production

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Introduction

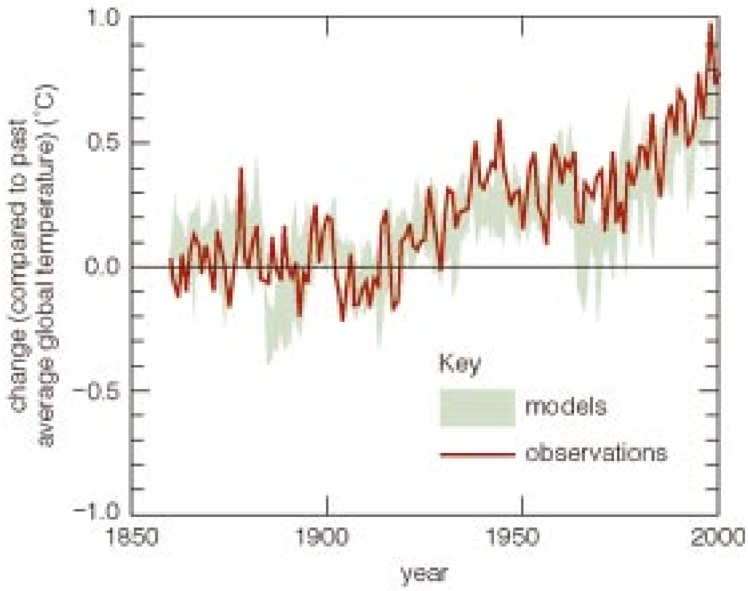
The unimpeded growth of greenhouse gas emission is raising the earth's temperature. The consequences include melting glaciers, more precipitation, more and more extreme weather events, and shifting seasons. The accelerating pace of climate change, combined with global population and income growth, threatens food security everywhere. Agriculture is extremely vulnerable to climate change. Higher temperature eventually reduce yields of desirable crops while encouraging weed and pest proliferation. Changes in precipitation pattern increase the likelihood of short-run crop failure and long-run production declines. Although there will be gains in some crops in some regions of the world, the overall impacts of climate change on agriculture are expected to be negative, threatening global food security. Populations in the developing world, which are already vulnerable and food insecure, are likely to be the most seriously affected. In 2005, nearly half of the economically active population in developing countries—2.5 billion people—relied on agriculture for its livelihood. Today, 75 percent of the world's poor live in rural areas. Modeling of crop growth under climate change with insights from an extremely detailed global agriculture model, using two climate scenarios to simulate future climate. suggest that agriculture and human well-being will be negatively affected by climate change. In developing countries, climate change will cause yield decline for the most important crops. South Asia will be particularly hard hit. Climate change will have varying effects on irrigated yields across regions, but irrigated yields for all crops in South Asia will experience large decline. Climate change will result in additional price increase for the most important agricultural crops–rice, wheat, maize, and soybeans. Higher feed prices will result in higher meat prices. As a result, climate change will reduce the growth in meat consumption slightly and cause a more substantial fall in cereals consumption. Calorie availability in 2050 will not only be lower than that in the no–climate-change scenario but also it will decline relative to 2000 levels throughout the developing world. By 2050, the decline in calorie availability will increase child malnutrition by 20 percent relative to a world with no climate change. Climate change will eliminate much of the improvement in child malnourishment levels that would occur with no climate change. Thus, aggressive agricultural productivity investments of US$ 7.1–7.3 billion are needed to raise calorie consumption enough to offset the negative impacts of climate change on the health and well-being of children.

The accelerating changes in the earth's environment are occuring due to the growth in human population through increasing level of resource consumption, changes in the technologies and socio-political organizations. Changes in global climatic scenarios, which affect agriculture are: a) Changes in land use and land cover b) World wide decline of biodiversity c) Changes in atmospheric composition of gases, and d) Changes in climate. One of the major driving forces for global climate change is the rapid increase in the greenhouse gas content in the atmosphere. The percapita CO_2 emission from south Asia was 0.47 Tg (Tera gram) during 1995 whereas, it's projected value is 0.90 Tg for 2050. The total regional emission of GHG (in CO_2 equivalents) is 3 percent of the global total emission. Its annual growth rate is as high as 6 per cent for India, 8 per cent for Bangladesh and 10 per cent for Pakistan (IPCC, 2001).

These changes to the environment will most likely cause negative effects on society, such as poor health and decreasing economic development. However, some scientists argue that the global warming we are experiencing now is a natural phenomenon, and is a part of Earth's natural cycle. Presently, lot of debate is going on the theory, but one thing is certain, the world has been emitting greenhouse gases at extremely high rates and has shown only small signs of reducing emissions until the last few years. After the 1997 Kyoto Protocol, steps have finally been taken for reducing emissions.

What is Greenhouse effect?

The "greenhouse effect" is the heating of the Earth due to the presence of greenhouse gases. It is named this way because of a similar effect produced by the glass panes of a greenhouse. Shorter-wavelength solar radiation from the sun passes through Earth's atmosphere and then is absorbed by the surface of the Earth, causing it to warm. Part of the absorbed energy is then radiated back to the atmosphere as long wave infrared radiation. Little of this long wave radiation escapes back into space; the radiation cannot pass through the greenhouse gases in the atmosphere. The greenhouse gases selectively transmit infrared waves, trapping some and allowing some to pass through into space. The greenhouse gases absorb these waves and re-emit the waves downward, causing the lower atmosphere warming. Fourth assessment report of IPCC says that coastal belts of India are more prone to devastating impacts of global warming. The rising sea levels due to climate change may force many poor communities in low-lying coastal areas to move to higher ground. The livelihood of coastal people is mainly dependent on fishery, forestry and aquaculture. Hence, the displacement of people will result in competition between migrants and original inhabitants for both accesses to land and livelihood. Changing sea-ecosystem will further aggravate the misery of small fishing communities as the quantum of fish catch will diminish due to spread of algae and other diseases.



(Source: NCDC/NESDIS/NOAA)

Greenhouse gas overview

In order, Earth's most abundant greenhouse gases are: water vapor, carbon dioxide, methane, nitrous oxide, ozone and chlorofluorocarbons.

a) **Carbon dioxide (CO_2)**: Carbon dioxide enters the atmosphere through burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and as a result of other chemical reactions (e.g., manufacture of cement). Carbon dioxide is removed from the atmosphere (or "sequestered") when it is absorbed by plants as part of the biological carbon cycle.

b) **Methane (CH_4)**: Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills.

c) **Nitrous oxide (N_2O)**: Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.

d) **Fluorinated gases**: Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for ozone-depleting substances (i.e., CFCs, HCFCs, and halons). These gases are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as High Global Warming Potential gases ("High GWP gases").

Global warming potential

The global warming potential (GWP) depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime. GWP is measured relative to the same mass of CO_2 and evaluated for a specific timescale. Thus, if a gas has a high GWP on a short time scale (say 20 years) but has only a short lifetime, it will have a large GWP on a 20 year scale but a small one on a 100 year scale. Conversely, if a molecule has a longer atmospheric lifetime than CO_2 its GWP will increase with the timescale considered.

Examples of the atmospheric lifetime and GWP for several greenhouse gases include:

a) **Carbon dioxide** has a variable atmospheric lifetime, and cannot be specified precisely (Solomon *et al*., 2007). Recent work indicates that recovery from a large input of atmospheric CO_2 from burning fossil fuels will result in an effective lifetime of tens of thousands of years (Archer and Ganopolski, 2005). Carbon dioxide is defined to have a GWP of 1 over all time periods.

b) **Methane** has an atmospheric lifetime of 12 ± 3 years and a GWP of 72 over 20 years, 25 over 100 years and 7.6 over 500 years. The decrease in GWP at longer times is because methane is degraded to water and CO_2 through chemical reactions in the atmosphere.

c) **Nitrous oxide** has an atmospheric lifetime of 114 years and a GWP of 289 over 20 years, 298 over 100 years and 153 over 500 years.

d) **CFC-12** has an atmospheric lifetime of 100 years and a GWP of 11000 over 20 years, 10900 over 100 years and 5200 over 500 years.

e) **HCFC-22** has an atmospheric lifetime of 12 years and a GWP of 5160 over 20 years, 1810 over 100 years and 549 over 500 years.

f) **Tetrafluoromethane** has an atmospheric lifetime of 50,000 years and a GWP of 5210 over 20 years, 7390 over 100 years and 11200 over 500 years.

g) **Hexafluoroethane** has an atmospheric lifetime of 10,000 years and a GWP of 8630 over 20 years, 12200 over 100 years and 18200 over 500 years.

h) **Sulphur hexafluoride** has an atmospheric lifetime of 3,200 years and a GWP of 16300 over 20 years, 22800 over 100 years and 32600 over 500 years.

i) **Nitrogen trifluoride** has an atmospheric lifetime of 740 years and a GWP of 12300 over 20 years, 17200 over 100 years and 20700 over 500 years.

Greenhouse effects on Earth's atmosphere

The contribution to the greenhouse effect by a gas is affected by both the characteristics of the gas and its abundance. For example, on a molecule-for-molecule basis, methane is about eight times stronger greenhouse gas than carbon dioxide (Houghton, 2005), but it is present in much smaller concentrations so that its total contribution is smaller.

Forth Assessment Report compiled by the IPCC "changes in atmospheric concentrations of greenhouse gases and aerosols, land cover and solar radiation alter the energy balance of the climate system", concluded that "increases in anthropogenic greenhouse gas concentrations is very likely to have caused most of the increases in global average temperature since the mid-20th century" (Kiehl and Trenberth, 1997), where "most of" is defined as more than 50%.

Gas	Pre-industrial level	Current level	Increase since 1750	Radiative forcing (W/m^2)
Carbon dioxide	280 ppm	387 ppm	107 ppm	1.46
Methane	700 ppb	1745 ppb	1045 ppb	0.48
Nitrous oxide	270 ppb	314 ppb	44 ppb	0.15
CFC-12	0	533 ppt	533 ppt	0.17

Anthropogenic greenhouse gases

The main sources of greenhouse gases due to human activity are:

a) Burning of fossil fuels and deforestation leading to higher carbon dioxide concentrations. Land use change (mainly deforestation in the tropics) account for up to one third of total anthropogenic CO_2 emissions (Kiehl and Trenberth, 1997).

b) Livestock enteric fermentation and manure management (Steinfeld *et al*., 2006) in paddy rice farming, land use and wetland changes, pipeline losses, and covered vented landfill emissions lead to higher atmospheric methane concentrations. Many of the newer style fully vented septic systems that enhance and target the fermentation process also are sources of atmospheric methane.

c) Use of chlorofluorocarbons (CFCs) in refrigeration systems, and use of CFCs and halons in fire suppression systems and manufacturing processes.

d) Agricultural activities, including the use of fertilizers, which lead to higher nitrous oxide (N_2O) concentrations.

The seven sources of CO_2 from fossil fuel combustion are (with percentage contributions for 2000–2004):

1. Solid fuels (e.g., coal): 35%
2. Liquid fuels (e.g., gasoline, fuel oil): 36%
3. Gaseous fuels (e.g., natural gas): 20%
4. Flaring gas industrially and at wells: <1%
5. Cement production: 3%
6. Non-fuel hydrocarbons: < 1%
7. The "international bunkers" of shipping and air transport not included in national inventories: 4%

The US Environmental Protection Agency (EPA) ranks the major greenhouse gas contributing end-user sectors in the following order: industrial, transportation, residential, commercial and agricultural (Raupach *et al.*, 2007). Major sources of an individual's greenhouse gas include home heating and cooling, electricity consumption, and transportation.

Corresponding conservation measures are improving home building insulation, installing geothermal heat pumps and compact fluorescent lamps, and choosing energy-efficient vehicles. On December 7, 2009, the US Environmental Protection Agency released its final findings on greenhouse gases, declaring that "greenhouse gases (GHGs) threatened the public health and welfare of the American people". The findings applied to the same "six key well-mixed greenhouse gases" named in the Kyoto Protocol: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

Role of water vapor

Water vapor accounts for the largest percentage of the greenhouse effect, between 36% and 66% from water vapor alone, and between 66% and 85% when factoring in clouds. However, the warming due to the greenhouse effect of cloud cover is, at least in part, mitigated by the change in the earth's albedo. According to NASA, "The overall effect of all clouds together is that the Earth's surface is cooler than it would be if the atmosphere had no clouds."

Greenhouse gas emissions: Relevant to radiative forcing

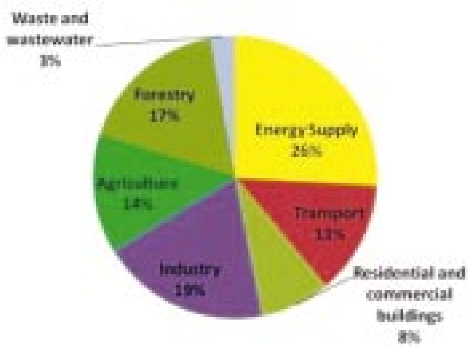
Gas	Current (1998) amount by volume	Increase (ppm) over pre-industrial (1750)	Increase (%) over pre-industrial (1750)	Radiative forcing (W/m^2)
CO_2	365ppm (383 ppm, 2007)	87 ppm (105 ppm, 2007.01)	31% (38%, 2007.01)	1.46 (~1.53, 2007.01)
CH_4	1745 ppb	1045 ppb	67%	0.48
N_2O	314 ppb	44 ppb	16%	0.15

Gas	Current (1998) amount by volume	Radiative forcing (W/m^2)
CFC-11	268 ppt	0.07
CFC-12	533 ppt	0.17
CFC-113	84 ppt	0.03
Carbon tetrachloride	102 ppt	0.01
HCFC-22	69 ppt	0.03

(Source: IPCC radiative forcing report 1994 updated (to 1998) by IPCC TAR table 6.1 Climate Change 2001: The Scientific Basis of Current Greenhouse Gas Concentrations)

Global GHG emissions by sector

Agriculture is particularly vulnerable to climate change. Projections to 2050 suggest both an increase in global mean temperature and increased weather variability, with implications for the type and distribution of agricultural production worldwide. Climate change will also worsen the living conditions for many who are already vulnerable, particularly in developing countries because of lack of assets and adequate insurance coverage.



These impacts highlight key policy issues, including the need to produce more food for an increasing population. Projections of more than 9 billion people in 2050 suggest that food production will need to double from current levels.

Impact of climate change on OECD agriculture

Temperature Change	Impact
$+1^0$ to $+2^0$C	Some increase in yield Cold climate alleviated Yield reduction in some latitudes (without adaptation) Seasonal increase in heat stress for livestock
$+2^0$ to $+3^0$C	Potential increase in yield due to CO_2 fertilization (but likely to be offset by other factors) Moderate production losses of pigs and confined cattle Increased heat stress Yield of all crops fall in low latitudes (without adaptation)
$+3^0$ to $+ 5^0$C	Maize and wheat yields fall regardless of adaptation in low latitudes High production losses of pigs and confined cattle Increased heat stress and mortality in livestock

Source: Adopted from IPCC AR4 Working group II

Removal of green house gases

In order to limit future global warming to a 2°C temperature increase as recommended by IPCC, anthropogenic GHG emissions will have to decrease globally by at least 50% by 2050 from 1990 levels. Agriculture is not currently subject to emissions caps, although several OECD countries are already implementing mitigation action plans.

In addition to reducing its own emissions, carbon sequestration in agricultural soils can play an important role in offsetting emissions from other sectors. Some agricultural GHG mitigation options are cost competitive with a number of non-agricultural options in achieving long-term climate objectives.

Quantifying GHG emissions from agricultural activities is complex. First, the atomistic nature of production (many individual farmers) in a wide range of geographic and climatic conditions means that emissions are not only highly variable but also difficult and costly to measure precisely. Second, there continues to be a great deal of scientific uncertainty as GHG emissions from agriculture are subject to a complex interplay of many factors such as climate, soil type, slope, and production practices.

Accounting for the indirect land use changes arising from agricultural production is another important challenge. The recent global surge in food prices highlighted the importance of agricultural policies for world food and energy markets. In particular, the links between production of biofuels from feedstock (in many cases subsidised), consequent land use changes, and food prices demonstrate the importance of foreseeing the range of consequences.

Greenhouse gases can be removed from the atmosphere by various processes:

a) As a consequence of physical change (condensation and precipitation remove water vapor from the atmosphere).
b) As a consequence of chemical reactions within the atmosphere. For example, methane is oxidized by reaction with naturally occurring hydroxyl radical, OH^{-1} and degraded to CO_2 and water vapor (CO_2 from the oxidation of methane is not included in the methane global warming potential). Other chemical reactions include solution and solid phase chemistry occurring in atmospheric aerosols.
c) As a consequence of a physical exchange between the atmosphere and the other compartments of the planet. An example is the mixing of atmospheric gases into the oceans.
d) As a consequence of a chemical change at the interface between the atmosphere and the other compartments of the planet. This is the case for CO_2, which is reduced by photosynthesis of plants, and which, after dissolving in the oceans, reacts to form carbonic acid and bicarbonate and carbonate ions.
e) As a consequence of a photochemical change. Halocarbons are dissociated by UV light releasing Cl and F as free radicals in the stratosphere with harmful effects on ozone (halocarbons are generally too stable to disappear by chemical reaction in the atmosphere).

Climate change response strategies for agriculture

As a result of greenhouse gases already in the atmosphere from past and current emissions, our planet is already committed to at least as much warming over the 21st century as it has experienced over the 20th century (0.75°C). This implies that in addition to mitigation, adaptation to the anticipated warming is essential. Possible strategies for adapting food and forestry production to climate change have been identified (Schmidhuber and Tubiello, 2007).

Agriculture in the 21st century will therefore, be undergoing significant challenges, arising largely from the need to increase the global food and timber supply for a world nearing a population of over 10 billion, while adjusting and contributing to respond to climate change. Success in meeting these challenges will require a steady stream of technical and institutional innovations, so that adaptation strategies to climate change are consistent with efforts to safeguard food security and maintain ecosystem services, including mitigation strategies that provide carbon sequestration, and offsets under sustainable land management (Easterling, 2007).

Physiological changes and agro-ecological impacts

Climate change will affect agriculture and forestry systems through a number of critical factors

a) Rising temperatures, can lead to negative impacts such as added heat stress, especially in areas at low-to-mid latitudes which are already at risk today. However, they can also lead to positive impacts, such as an extension of the growing season in high-latitude regions that are currently limited by low temperatures.
b) Elevated atmospheric CO_2 concentrations, which tend to increase plant growth and yield, and may improve water use efficiency, particularly in so-called C_3 carbon fixation plants such as wheat, rice, soybean, and potato. The impact on C_4 carbon fixation plants, such as maize, sugarcane, and many tropical pasture grasses, is not as pronounced due to different photosynthetic pathways (Easterling, 2007). How much agricultural plants in fields and trees in plantation forests benefit from elevated CO_2, given a number of limiting factors such as pests, soil and water quality, crop-weed competition, remains an open question.
c) Changes in precipitation patterns, especially changes in frequency of the extremes, with both droughts and flooding events projected to increase in coming decades, leading to possible negative consequences for land-production systems. At the same time, a critical factor affecting plant productivity will be linked to simultaneous temperature and precipitation changes that influence soil water status and the ratio of evaporative demands to precipitation. All these factors, and their key interactions, must be considered together, across crops in different regions, in order to fully understand the impact that climate change will have on agriculture. Importantly, the experimental measurements of crop and pasture responses to changes in climate variables are still limited to small-scale plots, therefore, results are difficult to extrapolate to the field and farm level. As a consequence, current computer models of plant production, although quite advanced in their handling of soil-plant-atmospheric dynamics as well as crop management, lack realistic descriptions of key limiting factors to real fields and farm operations. Therefore, the potential for negative impacts under climate change is not fully explored by current regional and global projections.

Key interactions that are currently poorly described by crop and pasture models include:

a) No linearity and threshold effects in response to increases in the frequency of extreme events under climate change;
b) Modification of weed, pest, and disease incidence, including weed-crop competition;
c) Large-scale field response of crops to elevated CO_2 concentration; and
d) Interactions of climate and management variables, including effects of elevated CO_2 levels.

Regardless of these uncertainties, there is no doubt that plant development, growth, yield, and ultimately the production of crop and pasture species will be impacted by, and will respond to, increases in atmospheric CO_2 concentration, higher temperatures, altered precipitation and evapo-transpiration regimes, increased frequency of extreme temperature and precipitation events, as well as weed, pest and pathogen pressures (IPCC, 2001). Recent research has helped to better quantify the potential outcome of these key interactions.

Impacts

Higher temperature

The Fourth Assessment Report of the IPCC (2007) provides a number of important considerations on the overall impacts of higher temperature on crop responses. The report suggests that at the plot level, and without considering changes in the frequency of extreme events, moderate warming (i.e., what may happen in the first half of this century) may benefit crop and pasture yields in temperate regions, while it would decrease yields in semiarid and tropical regions. Modeling studies indicate small beneficial effects on crop yields in temperate regions corresponding to local mean temperature increases of 1–3°C and associated CO_2 increase and rainfall changes. By contrast, in tropical regions, models indicate negative yield impacts for the major crops even with moderate temperature increases (1–2°C). Further warming projected for the end of the 21st century has increasingly negative impacts in all regions (Cline, 2007; Kimball *et al*., 2002).

At the same time, farm-level adaptation responses may be effective at low to medium temperature increases, allowing coping with up to 1–2°C local temperature increases; an effect that may be considered as "buying time" (Cline, 2007; Kimball *et al.,* 2002). Increased frequency of heat stress, droughts, and floods negatively affect crop yields and livestock beyond the impacts of mean climate change, creating the possibility for surprises, with impacts that are larger, and occurring earlier, than predicted using changes in mean variables alone.

Elevated atmospheric CO_2 levels

Studies conducted over the last 30 years have confirmed that plant biomass and yield tend to increase significantly as CO_2 concentrations increase above current levels. Such results are found to be robust across a variety of experimental settings—such as controlled environment closed chambers, greenhouses, open and closed field top chambers, as well as Free-Air Carbon dioxide Enrichment experiments (FACE). Elevated CO_2 concentrations stimulate photosynthesis, leading to increased plant productivity and modified water and nutrient cycles (Nowak *et al*., 2004). Experiments under optimal conditions show that doubling the atmospheric CO_2 concentration increases leaf photosynthesis by 30–50 percent in C_3 plant species and by 10–25 percent in C_4 species, despite feedbacks that reduce the response of leaf photosynthesis by elevated atmospheric CO_2 concentrations (Ainsworth and Long, 2005). Increases in above ground biomass at 550 ppm CO_2 for trees are up to 30 percent.

Plant physiologists and modelers recognize, however, that the effects of elevated CO_2, as measured in experimental settings and subsequently implemented in models, may overestimate actual field and farm-level responses, due to limiting factors such as pests, weeds, nutrients, competition for resources, and soil, water and air (Tubiello *et al.*, 2007).

Interactions of elevated CO_2 with temperature and precipitation

High temperature during the critical flowering period of a crop may lower otherwise positive CO_2 effects on yield by reducing grain number, size, and quality (Tubiello and Fischer, 2007). Increased temperature during the growing period may also reduce CO_2 effects indirectly, by increasing water demand. For example, yield of rainfed wheat grown at 450 ppm CO_2 increased up to 0.8°C warming, but declined beyond 1.5°C warming; additional irrigation was needed to counterbalance these negative effects (Centritto, 2005). Future CO_2 levels may favour C_3 plants over C_4; yet the opposite is expected under associated temperature increases. The net effects remain uncertain. Because of the key role of water in plant growth, climate impacts on crops significantly depend on the future precipitation scenario. Because more than 80 percent of total agricultural land—and close to 100 percent pastureland—is rainfed, Global Climate Model (GCM)-projected changes in precipitation will often shape both the direction and magnitude of the overall impacts (Olesen and Bindi, 2002). In general, changes in precipitation, and more specifically in evapo-transpiration to precipitation ratios, modify ecosystem productivity and function, particularly in marginal areas; higher water-use efficiency as a result of stomatal closure; greater root densities under elevated CO_2 may in some cases alleviate or even counterbalance drought pressures (Morgan *et al*., 2004; Centritto, 2005).

Interactions of elevated CO_2 with soil nutrients

Various FACE (Free air CO_2 enrichment) experiments confirm that high nitrogen content in the soil increases the relative response of crops to elevated atmospheric CO_2 concentrations (Nowak *et al*., 2004). They demonstrated that the yield response of C_3 plant species to elevated atmospheric CO_2 concentrations is not significant under low nitrogen levels, but increases over 10 years with high levels of nitrogen rich fertilizer application. In fertile grasslands, legumes benefit more from elevated atmospheric CO_2 concentrations when compared to species that do not fix nitrogen (Ross *et al.*, 2004.). Therefore, to capitalize on the benefits of elevated CO_2 levels, declines in the availability of nitrogen may be prevented by biological N_2-fixation. However, other nutrients, such as phosphorus, an important nutrient for biological N-fixation, may act as a limiting factor and restrict legume growth response to higher atmospheric CO_2 concentrations.

Interactions with air pollutants

Tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth, and species composition. Additionally, as global ozone exposures increase over this century, direct and indirect interactions with climate change and elevated CO_2 levels will further modify plant dynamics (Booker *et al.*, 2005). Although several studies confirm previous findings that elevated CO_2 concentrations may ameliorate otherwise negative impacts from ozone, it is important to note that increasing ozone concentrations in the future, with or without climate change, will negatively impact plant production and possibly increase exposure to pest damage. Ultra Violet (UV)-B exposure is in general harmful to plant growth, knowledge on the interactions between UV-B exposure and elevated CO_2 is still incomplete, with some experimental findings suggesting that elevated CO_2 levels mitigate the negative effects of UV-B on plant growth, while others show no effect.

Vulnerability of carbon pools

Impacts of climate change on the land that is under human management for food and livestock have the potential to significantly affect the global terrestrial carbon sink and to further perturb atmospheric CO_2 concentrations. Furthermore, the vulnerability of organic carbon pools to climate change has important repercussions for land sustainability and climate mitigation actions. Future changes in carbon stocks and net fluxes would critically depend on land use planning-policies, forestation/reforestation, and so on—and management practices such as nitrogen fertilization, irrigation, and tillage, in addition to plant response to elevated CO_2. Recent experimental research confirms that carbon storage in soil organic matter pools is often increased under elevated CO_2, at least in the short term (Allard *et al*., 2005); yet the total soil carbon sink may become saturated at elevated CO_2 concentrations, especially when nutrient inputs are low (Gill, 2002). The effects of air pollution on plant function may indirectly affect carbon storage; recent research showed that tropospheric ozone resulted in significantly less carbon sequestration rates under elevated CO_2 (Rosenzweig, 2007) as a result of the negative effects of ozone on biomass productivity and changes to litter chemistry (Booker *et al.*, 2005). Finally, recent studies show the importance of identifying potential synergies between land-based adaptation and mitigation strategies, linking issues of carbon sequestration, emissions of greenhouse gases, land use change, and long-term sustainability of production systems within coherent climate policy frameworks (Antle, 2004). In addition, the predicted small global effects mask the fact that climate change is expected to disproportionately impact agricultural production in low-latitude, tropical developing countries, while some high-latitude, developed countries may benefit.

Impacts of climate change on irrigation water requirement

A few new studies have quantified the impacts of climate change on regional and global irrigation requirements, irrespective of the positive effects of elevated CO_2 on crop water use efficiency. Considering the direct impacts of climate change on crop evaporative demand, in the absence of any CO_2 effects, an increase of *net* crop irrigation requirement is estimated, that is, net transpiration losses, of 5 to 8 percent globally by 2070, and larger regional signals, for example, 15 percent in southeast Asia (Doll, 2002). In another study, that included the positive CO_2 effects on crop water use efficiency, increases in global net irrigation requirement of 20 percent by 2080 were projected, with larger impacts in developed regions, due to increased evaporative demands and longer growing seasons under climate change. Arnell (2004), has also projected increases in water stress—the ratio of irrigation withdrawals to renewable water resources—in the Middle East and Southeast Asia.

In developing countries like India, climate change could represent an additional stress on ecological and socioeconomic systems that are already facing tremendous pressure due to rapid urbanization, industrialization and economic development. With its huge and growing population, a 7500-km long densely populated and low-lying coastline, and an economy that is closely tied to its natural resource base, India is considerably vulnerable to the impacts of climate change.

The various studies conducted in the country have shown that the surface air temperatures in India are going up at the rate of 0.4°C per hundred years, particularly during the post-monsoon and winter season. Using models, modelers predict that mean winter temperatures will increase by as much as 3.2°C in the 2050s and 4.5°C by 2080s, due to greenhouse gases. Summer temperatures will increase by 2.2°C in the 2050s and 3.2°C in the 2080s.

Extreme temperatures and heat spells have already become common over Northern India, often causing loss of human life. In 1998 alone, 650 deaths occurred in Odisha due to heat waves. Climate change has had an effect on the monsoons too. India is heavily dependent on the monsoon to meet its agricultural and water needs, and also for protecting and propagating its rich biodiversity. Scientists at IIT, Delhi, have already noted subtle changes in the monsoon rain patterns. They also warned that India will experience a decline in summer rainfall by the 2050s, summer rainfall accounts for almost 70% of the total annual rainfall over India and is crucial to Indian agriculture. Relatively small climatic changes can cause large water resource problems, particularly in arid and semi-arid regions such as northwest India. This will have an impact on agriculture, drinking water and on generation of hydroelectric power.

Apart from monsoon rains, India uses perennial rivers, which originate and depend on glacial melt-water in the Hindukush and Himalayan ranges. Since the melting season coincides with the summer monsoon season, any intensification of the monsoon is likely to contribute to flood disasters in the Himalayan catchments. Rising temperatures will also contribute to the raising of snowline, reducing the capacity of this natural reservoir, and increasing the risk of flash floods during the wet season.

Increased temperatures will impact agricultural production. Higher temperature reduce the total duration of a crop cycle by inducing early flowering, thus shortening the ‘grain fill’ period. The shorter the crop cycle, the lower the yield per unit area.

A trend of sea level rise of 1 cm per decade has been recorded along the Indian coast. Sea level rise due to thermal expansion of seawater in the Indian Ocean is expected to be about 25-040 cm by 2050. This could inundate low lying areas, down coastal marshes and wetlands, erode beaches, exacerbate flooding and increase the salinity of rivers, bays and aquifers.

Flooding, erosion and salt intrusion will threaten deltas. Loss of coastal mangroves will have an impact on fisheries. The major delta area of the Ganga, Brahmaputra and Indus rivers, which have large populations reliant on riverine resources will be affected by changes in water regimes, salt water intrusions and land loss.

Increase in temperatures will result in shifts of lower altitude tropical and subtropical forests to higher altitude temperate forest regions, resulting in the extinction of some temperate vegetation types. Decrease in rainfall and the resultant soil moisture stress could result in drier teak dominated forests replacing sal trees in central India. Increased dry spells could also place dry and moist deciduous forests at increased risk from forest fires.

Medical Science suggests that the rise in temperature and change in humidity will adversely affect human health in India. Heat stress could result in heat cramps, heat exhaustion; heal stroke, and damage physiological functions, metabolic processes and immune systems. Increased temperatures can increase the range of vector borne diseases such as malaria, particularly in regions where minimum temperatures currently limited pathogen and vector development. Climate change will make monsoons unpredictable; as a result, rain-fed wheat cultivation in South Asia will suffer in a big way and the total cereal production will go down. The crop yield per hectare will be hit badly, causing food insecurity and loss of livelihood.

R. K. Pachauri, chairman of the IPCC estimated that a rise of 0.5 degree celsius in winter temperatures could cause a 0.45 tonne per hectare fall in India's wheat production. The average per hectare production in India is 2.6 tonnes. Worse still, Pachauri said, total agricultural land will shrink and the available land may not remain suitable for the present crops for too long. Farmers have to explore options of changing crops suitable to weather. He also pointed out that climatic changes could lead to major food security issues for a country like India. The report also predicts huge coastal erosion due to a rise in sea levels of about 40 cm resulting from faster melting of glaciers in the Himalayan and Hindukush ranges. It can affect half-a-million people in India because of excessive flooding in coastal areas and also can increase the salinity of ground water in the Sunder bans and surface water in coastal areas. India needs to sustain an 8 to 10 per cent economic growth rate, over the next 25 years, if it is to eradicate poverty and meet its human development goals, according to a 2006 report on an integrated energy policy prepared by an expert committee of the Planning Commission. Consequently, the country needed at the very least to increase its primary energy supply three or four -fold over the 2003-04 level.

Impact of climate change on agriculture - factsheet on Asia

- According to the study, the Asia-Pacific region will experience the worst effect on rice and wheat yields worldwide, and decreased yields could threaten the food security of 1.6 billion people in South Asia.

- The crop model indicates that in South Asia, average yields in 2050 for crops will decline from 2000 levels by about 50 percent for wheat, 17 percent for rice, and about 6 percent for maize because of climate change.
- In East Asia and the Pacific, yields in 2050 for crops will decline from 2000 levels by up to 20 percent for rice, 13 percent for soybean, 16 percent for wheat, and 4 percent for maize because of climate change.
- With climate change, average calorie availability in Asia in 2050 is expected to be about 15 percent lower and cereal consumption is projected to decline by as much as 24 percent compared to a no climate change scenario.
- In a no-climate change scenario, the number of malnourished children in South Asia would fall from 76 to 52 million between 2000 and 2050, and from 24 to 10 million in East Asia and the Pacific. Climate change will erase some of this progress, causing the number of malnourished children in 2050 to rise to 59 million in South Asia and to 14 million in East Asia and the Pacific, increasing the total number of malnourished children in Asia by about 11 million.
- To counteract the effects of climate change on nutrition, South Asia requires additional annual investments of 1.5 billion USD in rural development, and East Asia and the Pacific require almost 1 million USD more. Over half of these investments in both regions must be for irrigation expansion.

Source: International Food Policy Research Institute, *Climate Change: Impact on Agriculture and Costs of Adaptation*, 2009

Additional facts

- The Asian countries most vulnerable to climate change are Afghanistan, Bangladesh, Cambodia, India, Lao PDR, Myanmar, and Nepal.
- Afghanistan, Bangladesh, India, and Nepal are particularly vulnerable to declining crop yields due to glacial melting, floods, droughts, and erratic rainfall, among other factors.
- Asia is the most disaster-afflicted region in the world, accounting for about 89 percent of people affected by disasters worldwide.
- More than 60 percent of the economically active population and their dependents—2.2 billion people—rely on agriculture for their livelihoods in developing parts of Asia.

In responding to the future challenges for agriculture of addressing climate change and increasing food demand, a coherent policy approach is needed that:

- Ensures a stable policy environment that sends clear signals to consumers and producers about the costs and benefits of GHG mitigating/sequestering activities.
- Provides a real or implicit price of carbon to create incentives for producers and consumers to invest in low-GHG products, technologies and processes.
- Fosters the application of existing technologies and invest in R&D for new technologies to reduce GHG emissions and increase productivity.

- Builds capacity to better understand and measure the GHG impact of agriculture for monitoring progress relative to national and international climate change goals.
- Facilitates adaptation by increasing producer resilience to climate change, and that compensate the most vulnerable groups.

Following Copenhagen, the OECD will continue to examine the role of land use change in agriculture (and the links with forestry), develop tools to analyze the design and implementation of cost effective policies so that agriculture can adapt to and mitigate climate change, and facilitate the sharing of experiences amongst countries on policies to address climate change in agriculture.

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Climate Change Impact on Indian Agriculture and Adaptation Strategies

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Climate change has become the talk of the day everywhere, be it international, regional and national arena and this phenomenon has got so much attention and importance that noble prize was awarded to Ale Gore and Intergovernmental Panel on Climate Change (IPCC) for their extensive work on climate change in 2007. IPCC in its recently released report has confirmed that global atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and other green house gases (GHGs) have increased markedly as a result of human activities since 1750. The CO_2, CH_4 and N_2O concentrations in atmosphere were 280 ppm, 715 ppb and 270 ppb, respectively in 1750 AD. In 2005, these values have became 379 ppm, 1774 ppb and 319 ppb, respectively. The increase of GHGs was 70% between 1970 and 2004. The major cause for the increase of CO_2 is the fossil fuel use and land use change, while those of CH_4 and N_2O are primarily due to agriculture (IPCC, 2007a) (Fig 1 and Fig 3). Per capita GHGs emission of some countries are given in table-1.

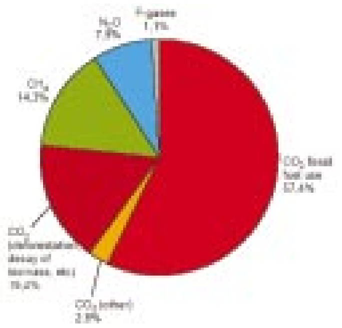


Fig 1 Emissions from different sources

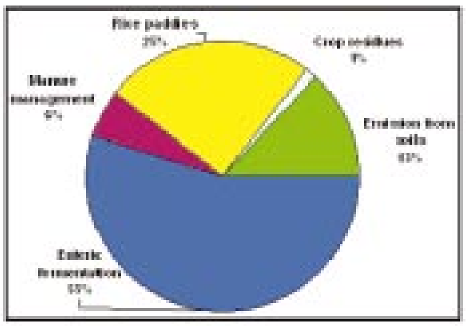


Fig 2 Relative contribution of different sectors in agriculture to GHG emissions
(Source: NATCOM, 2004)

Table 1 A comparison of India's per capita GHG emission with some other countries

Country	Per-Capita CO_2 emissions (metric tons)
USA	20.01
EU	9.40
Japan	9.87
China	3.60
Russia	11.71
India	1.02
World Average	4.25

These increases in GHGs have resulted in warming of the climate system by 0.74^0C between 1906 and 2005. Eleven of the twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface since 1850. This has in turn resulted in the increased average temperature of global ocean, rise in sea level, decline in glaciers and snow cover. It has also resulted in increase in the frequency of droughts, as well as heavy precipitation events over most of land areas in the recent time. IPCC has projected that temperature increase by the end of this century is likely to be in the range of 2.0 to 4.5^0C. They also projected the sea level rise by the end of the century is likely to be 0.18 to 0.59 m (IPCC, 2007a). Climate change, in many parts of the world, adversely affected socio-economic sectors, including water resources, agriculture, forestry, fisheries and human settlements, ecological systems and human health, especially in developing countries due to their vulnerability.

Indian agriculture and climate change

India is a large developing country with nearly 700 million rural population that directly depends on climate sensitive sectors (agriculture, forests and fisheries) and natural resources (such as water, biodiversity, mangroves, coastal zones, grasslands) for their subsistence and livelihoods. Further, the adaptive capacity of dry land farmers, forest dwellers, fisher folk and nomadic shepherds is very low. Climate change is likely to impact all the natural ecosystems as well as socio-economic systems as per the National Communications Report of India to the UNFCCC (Dwivedi, 2011). In India, several studies have shown that temperature marked an increasing trend over the previous century; rainfall had no such significant change. However, at regional levels, the rainfall showed increasing or decreasing trends in the previous century (NATCOM, 2004). Variability of rainfall is found in the different parts of India in the last few decades. Surface air temperature for the period 1901-2000 indicates that a warming of 0.4°C over these 100 years. The spatial distribution indicates that there is significant warming trend over west coast, central India, interior peninsula and north east India. However, cooling

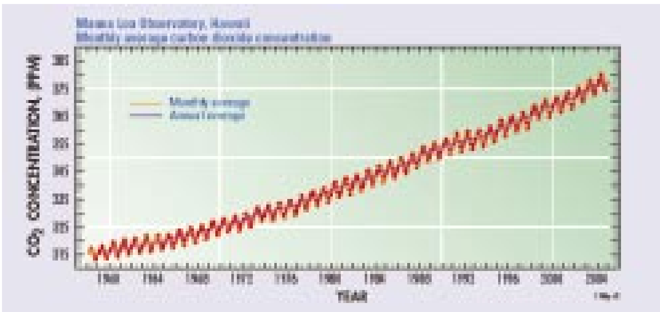
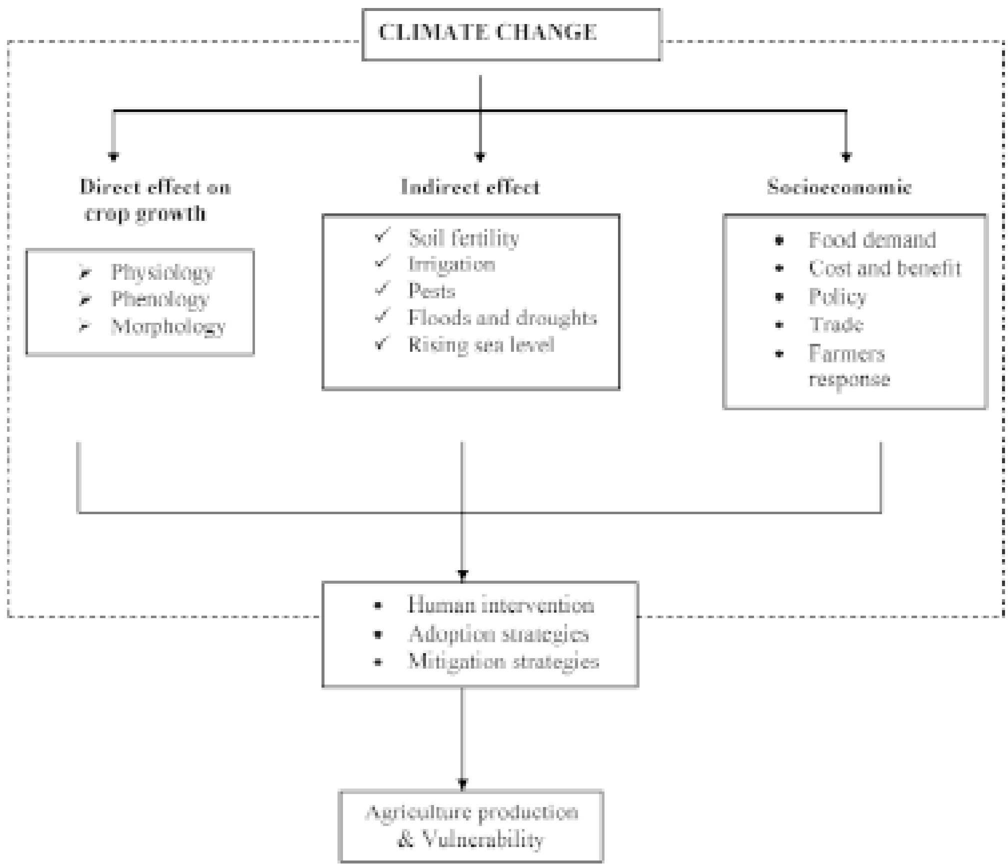


Fig 3 Increasing CO_2 concentration during last four decades (NATCOM, 2004)

trend was observed over northwest India and southern India. There are evidences that glaciers in the Himalayas are receding at a rapid pace (Kulkarni and Bahuguna, 2002; IPCC, 2007b). It is also projected that rainfall over India by the end of the century will increase by 15- 40% and mean annual temperature by 3-6°C (NATCOM, 2004). The warming will be more pronounced over land area and relatively greater over north India. The warming is also likely to be greater in winter and post monsoon season.

Impact of climate change on Indian agriculture

Climate change will have an economic impact on agriculture, including changes in farm profitability, prices, supply, demand and trade. The magnitude and geographical distribution of such climate-induced changes may affect our ability to expand the food production as required to feed the populace. Climate change may thus have far reaching effects on the patterns of trade among nations, development and food security.



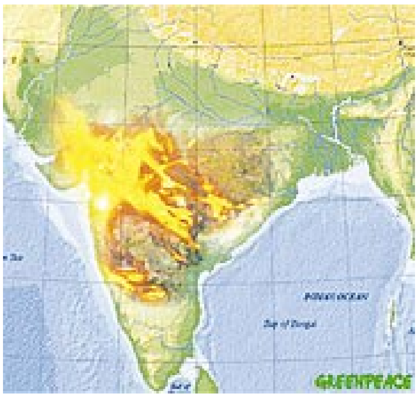


Fig 4 Different parts of India prone to regular drought and floods due to climate change

In the Indian context, Kumar and Parikh (2001) have estimated the macro level impacts of climate change using such an approach. They showed that under doubled carbon dioxide concentration levels in the later half of twenty-first century, the gross domestic product would decline by 1.4 to 3% points due to climate change. More significantly, they also estimated an increase in the proportion of population in the bottom income groups of the society in both rural and urban India as a result of climate change. Addressing the 83rd foundation day of Indian Council of Agricultural Research (ICAR), Dr. Man Mohan Singh the prime Minister of India said "The immediate problems that our farmers face relate to intra-seasonal variability of rainfall, extreme events and unseasonal rains. These aberrations cause heavy losses to our crops every year. There is therefore an urgent necessity for us to speed up our efforts to evolve climate-resilient crop varieties, cropping patterns and management practices."

Agriculture is sensitive to short-term changes in weather and to seasonal, annual and long-term variations in climate. Crop yield is the culmination of a diversified range of factors. Parameters like soil, seed, insect pest and diseases, fertilizers and agronomic practices exert significant influence on crop yield. The burgeoning population, along with human-induced climate change and environmental problems is increasingly proving to be limiting factors for enhancing farm productivity and ensuring food security for the rural poor. Very high temperatures will make it difficult, if not impossible, to store onion and potatoes. Preservation of vegetables and fruits would also become difficult. It would not be an exaggeration to say that the entire food processing industry would be in doldrums if the present cold storage equipment fails under the new climatic conditions. The paradox is, more is the refrigeration activities, the more will be the greenhouse emission gases and the greater would be the global warming.

Soil

The soil system responds to the short-term events such as episodic infiltration of rainfall and also undergoes long-term changes such as physical and chemical weathering due to climatic change. The potential changes in the soil forming factors directly resulting from global climate change would be in the organic matter supply, temperature regimes, hydrology and changes in the potential evapotranspiration. Both the organic matter and carbon to nitrogen ratio (C:N ratio) will diminish in a warmer soil temperature regime. Drier soil conditions will suppress both root growth and decomposition of organic matter and will increase vulnerability to erosion. Increased evaporation from the soil and accelerated transpiration from the plants themselves will cause soil moisture stress.

Insect pests, diseases and weeds

Incidence of insect pests and diseases would be most severe in tropical regions due to favorable climate/weather conditions, multiple cropping and availability of alternate hosts throughout the year. Climate change is likely to cause a spread of tropical and subtropical weed species into temperate areas and to increase the numbers of many temperate weed species currently limited by the low temperature at high latitudes.

Crop production and productivity

Estimates of impact of climate change on crop production could be biased depending upon the uncertainties in climate change scenarios, region of study, crop models used for impact assessment and the level of management. This study reports the results of a study where the impact of various climate change scenarios has been assessed on grain yields of irrigated rice with two popular crop simulation models- Ceres-Rice and ORYZA1N at different levels of N management. The results showed that the direct effect of climate change on rice crops in different agroclimatic regions in India would always be positive irrespective of the various uncertainties. Rice yields increased between 1.0 and 16.8% in pessimistic scenarios of climate change depending upon the level of management and model used. These increases were between 3.5 and 33.8% in optimistic scenarios. At current as well as improved level of management, southern and western parts of India which currently have relatively lower temperatures compared to northern and eastern regions, are likely to show greater sensitivity in rice yields under climate change (Aggarwal and Mall, 2002).

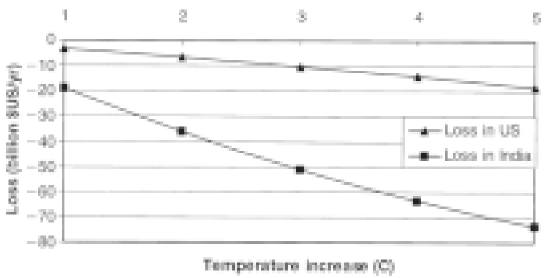


Fig 5 Warming impact in India: effect of temperature on farm value

(source: Dinar *et al*., 2002)

Overall, temperature increases are predicted to reduce rice yields. An increase of 2-4ºC is predicted to result in reduction in yields. Eastern regions are predicted to be most impacted by increased temperatures and decreased radiation, resulting in relatively fewer grains and shorter grain filling durations. By contrast, potential reductions in yields due to increased temperatures in Northern India are predicted to be offset by higher radiation, lessening the impacts of climate change (Fig 6). Although additional CO_2 can benefit crops, this effect may get nullified by an increase of temperature.

More recent studies done at the Indian Agricultural Research Institute, New Delhi indicated the possibility of loss of 4-5 million tons in wheat production with every degree rise of 1˚C temperature throughout the growing period even after considering benefits of carbon fertilization. This analysis assumes that irrigation would remain available in future at today's levels and there is no adaptation.

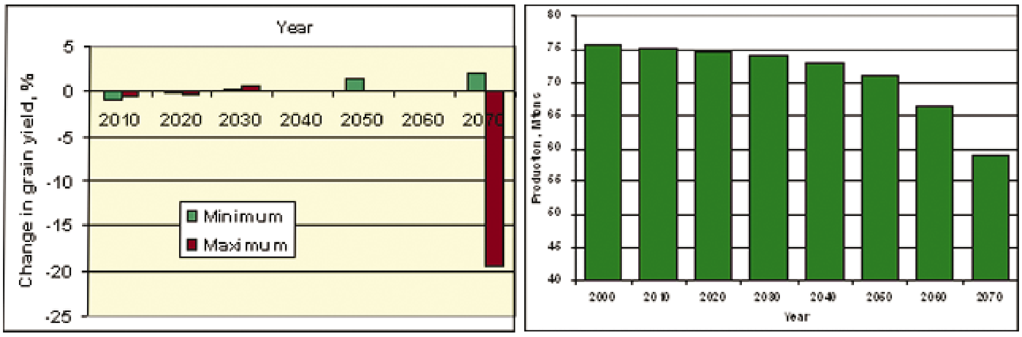


Fig 6 Impact of climate change on yield ability of rice and wheat (Aggarwal, 2003)

Fertilizer use efficiency

Fertilizer use efficiency in India is generally very low (15-30 %). Increasing temperature in future is likely to further reduce fertilizer use efficiency. This will lead to increased fertilizer requirement for meeting future food production demands. At the same time, greater fertilizer use leads to higher emissions of greenhouse gases. A large number of resource-poor farmers in tropics are not able to apply desired levels of fertilizers, irrigation and pest control. Simulation studies done at different levels of N management indicated that the crop response could vary depending upon the N management and the climate change scenario (Aggarwal, 2003).

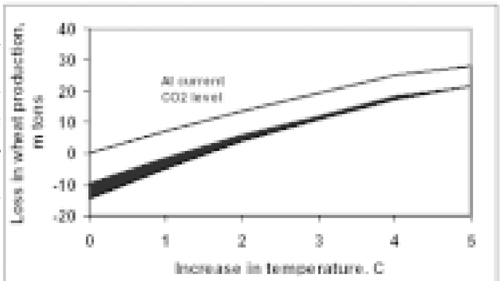


Fig 7 Projected loss in wheat production due to increasing temperature at current and 550 ppm CO_2 levels. The shaded area of the curve indicates losses that can be offset by adaptation options such as change in planting dates and variety

Crop physiology

The greenhouse gases CH_4, N_2O and chlorofluorocarbons (CFCs) have no known direct effects on plant physiological processes. Increase in the atmospheric air and soil temperature result in the variation of cytokinin. ABA (Abscissic acid) affects many physiological processes like water uptake, photosynthesis, respiration, assimilate partitioning and ultimately poor source sink relationship, which is evident by low yield.

C_3 plants (Rice, wheat) will always have advantages of elevated CO_2 compared to C_4 (sugarcane, millets and maize) and CAM (pineapple) plants. Many scientific studies revealed that the yield of C_3 plant increases with increase of CO_2 concentration in the atmosphere compared to C_4 plants. In the long run, increase of CO_2 concentration leads to increase in temperature, which again affects the yield of C_3 and other plants. Elevated CO_2 favors more vegetative growth through increased photosynthesis. Due to more CO_2, often more starch accumulates in the chloroplast and rupture of plastids which is visible through electron microscope observations. Leafy vegetable will have an advantage in the context of CO_2 in the production of more leaves.

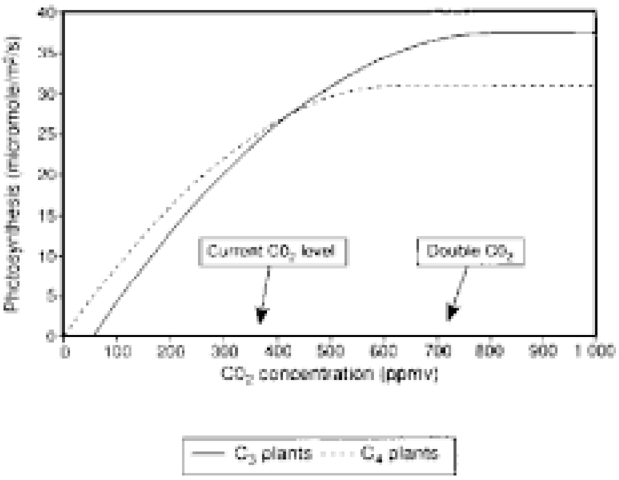


Fig 8 Effects of CO_2 concentrations on C_3 and C_4 plants (Wolfe and Erickson, 1993)

Vulnerability to climate change and adaptative capacity in India

O' Brien *et al*. (2004) tried to find out the vulnerability profile of India on the basis of adaptive capacity, sensitivity and exposure to climate change. Adaptive capacity was measured on the basis of biophysical, socioeconomic, and technological factors that influence agricultural production in 466 districts of India. This map shows higher degrees of adaptive capacity in districts located along the Indo-Gangetic Plains (except Bihar) and lower adaptive capacity in the interior portions of the country, particularly in the states of Bihar, Rajasthan, Madhya Pradesh, Maharashtra, Andhra Pradesh, and Karnataka (Fig 9).

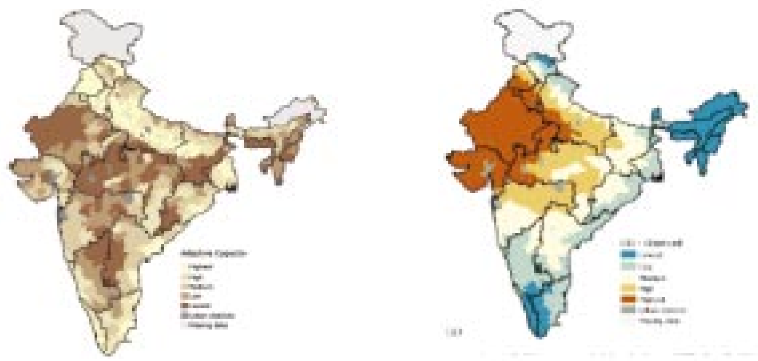


Fig 9 District-level mapping of (a) adaptive capacity and. (b) climate sensitivity in India, districts are ranked and presented as quantiles (O' Brien *et al.,* 2004)

To measure sensitivity under exposure to climate change, climate sensitivity index (CSI) was constructed that measures dryness and monsoon dependence, based on a girded data set for 1961–1990. The areas with high to very high climate sensitivity for agriculture are located in the semiarid regions of the country, including major parts of the states of Rajasthan, Gujarat, Punjab, Haryana, Madhya Pradesh and Uttar Pradesh (Fig 9).

Finally, to depict climate change vulnerability in India, they summed the district-level index of adaptive capacity with the index of climate sensitivity underexposure. The resulting climate vulnerability map (Fig10) represents current vulnerability to future climate change across the districts. The map depicts the range of relative climatic vulnerability at the district level in India. It is important to note that the districts with the highest (or lowest) climate sensitivity under the scenario of climate change used here are not necessarily the most (or least) vulnerable. For example, most districts in southern Bihar have only medium sensitivity to climate change, yet are still highly vulnerable to climate change as a the result of low adaptive capacity. By contrast, most districts in northern Punjab have very high sensitivity to climate change, yet are found to be only moderately vulnerable as the result of high adaptive capacity. Assessment of both adaptive capacity in combination with climate change sensitivity and exposure is thus crucial for differentiating relative vulnerability to climate change.

Concern for India

India should be concerned about climate change since this phenomenon might have substantial adverse impacts on her. Not all possible consequences of climate change are yet fully understood, but three main 'categories' of impacts are those on agriculture, sea level rise leading to submergence of coastal areas, and increased frequency of extreme events. Each of these may pose serious threats to India. However, these are long-term issues. The overriding immediate concern for India should be the fast pace at which negotiations are taking place on the climate front. India's main energy resource is coal. With the threat of climate change, India is called upon to change its energy strategy based on coal, its most abundant resource, and to use other energy sources (e.g., oil, gas, renewable and nuclear energy) which may turn out to be expensive. Thus, an immediate issue is to come up with a better negotiation strategy such that we have more freedom to decide which type of energy we use, how we generate power, how to reduce methane emissions by agricultural practices or forestry and so on. Negotiations are important for us as a means to reduce or postpone future vulnerability by getting the developed countries to reduce their emissions.

Adaptation strategies in agriculture

Any perturbation in agriculture can considerably affect the food security and thus increase the vulnerability of a large fraction of the resource poor population. We need to understand the possible coping strategies by different sections and different categories of producers to global climatic change. Such adaptation strategies would need to simultaneously consider the background of changing demand due to globalization and population increase and income growth, as well as the socio-economic and environmental consequences of possible adaptation options (Aggarwal *et al.*, 2004; Easterling *et al.*, 2004). Developing adaptation strategies exclusively for minimizing the negative impacts of climatic change may be risky in view of large uncertainties associated with its spatial and temporal magnitude. We need to identify 'no-regrets' adaptation strategies that may anyway be needed for sustainable development of agriculture. These adaptations can be at the level of individual farmer, society, farm, village, watershed, or at the national level. Some of the possible adaptation options are discussed below:

Research for C_4 strain

Scientists are working on a new strain of C_4 rice that could boost rice production by as much as 50 per cent, while potentially reducing the need for excessive water and fertilizers. The unique C_4 rice is expected to behave like corn and other plants that perform photosynthesis much more efficiently involving four carbon atoms — unlike the conventional rice strains, which use three carbon atoms. But significantly, the new strain is a genetically modified crop for which global acceptance is still extremely limited. And even if it finds acceptance in the years ahead, it has long way to go from experimental laboratories to successive field trials before being tried in real-world conditions.

Changes in land use and management

Effect of small changes in climatic parameters can often be managed reasonably well by altering dates of planting, spacing and input management. Development of alternate cultivars and farming systems (such as mixed cropping, crop-livestock) that are more adaptable to changes in the environment can further ease the pressure.

Development of resource conserving technologies

Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yields to the crop planted under normal conventional tillage over a diverse set of soil conditions. In addition, such resource conserving technologies restrict release of soil carbon into atmosphere thus mitigating increase of CO_2 in the atmosphere. Greater emphasis on water harvesting and improving regional as well as farm water use efficiency could help to face uncertain rainfall.

Improved land use and natural resource management policies and institutions

Adaptation to environmental change could be in the form of crop insurance, subsidies, pricing policies, and change in land use. Necessary provisions need to be included in the development plans to address these issues of attaining twin objectives of containing environmental changes and improving resource use productivity. Policies are needed that would encourage farmers to conserve water, energy and soil resources. For example, financial compensation/incentive for enriching soil carbon and increasing the efficiency of irrigation water through drip and sprinkler methods could encourage farmers to improve soil health, manage with less water, and assist in overall sustainable development. The National Mission for Sustainable Agriculture, which is one of the eight Missions under our National Action Plan on Climate Change also seeks to devise appropriate adaptation and mitigation strategies for ensuring food security, enhancing livelihood opportunities and contributing to economic stability at the national level (NAPCC, 2008).

Improved risk management though early warning system and crop insurance

The increasing probability of floods and droughts and other uncertainties in climate may seriously increase the vulnerability of resource-poor farmers to global climate change. Early warning systems and contingency plans can provide support to regional and national administration, as well as to local bodies and farmers to adapt. Policies that encourage crop insurance can provide protection to the farmers in the event their farm production is reduced due to natural calamities.

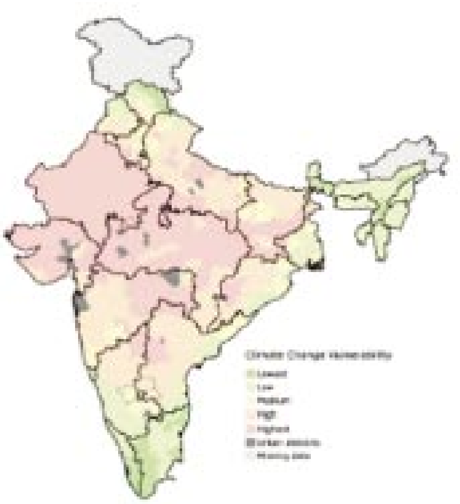


Fig 10 District-level mapping of climate change vulnerability
(O' Brien *et al.,* 2004)

Reducing dependence on agriculture

Although the share of agriculture in gross domestic product in India has declined to 16% but 58% population continues to remain dependent on this sector. Such trends have resulted in fragmentation and decline in the size of land holdings leading to inefficiency in agriculture and rise in unemployment, underemployment, and low volume of marketable surplus and, therefore, increased vulnerability to global climate change. Institutional arrangements, such as cooperatives and contract farming that can bring small and marginal farmers together for increasing production and marketing efficiencies are needed (Aggarwal, 2007).

Conclusion

Global climate change has considerable implications on Indian agriculture and hence on our food security and farmers' livelihood. We need to take steps urgently to increase our adaptive capacity. This would require increased support to adaptation research, developing regionally differentiated contingency plans for temperature and rainfall related risks, enhanced research on seasonal weather forecasts and their applications for reducing production risks, and evolving new land use systems, including heat and drought tolerant varieties, adapted to climatic variability and changes and yet meeting food demand. Strengthening current institutions and policy can also improve adaptive capacity. There is an urgent need to strengthen our surveillance mechanisms for various pests. We also need to support community partnerships in developing food and forage banks to manage scarcity during projected increased periods of drought and floods. Mechanisms for integrated management of rainwater, surface, and ground water need to be developed. Once a crop is planted, farmers need insurance cover to manage risks associated with extremes of temperature and precipitation events. Weather-derivatives should be provided to farmers at an early date. For mitigation of GHGs from agriculture, there is a need to renew focus on nitrogen fertilizer use efficiency with added dimension of nitrous oxides mitigation. Widespread testing of neem cake, and neem coated urea, known to inhibit N_2O emissions, would be rewarding. Studies are also needed to determine optimal size of livestock population in different agro-ecological regions considering national milk requirement, GHGs emissions and social issues. Financial incentives for improved land management including resource conservation/ enhancement (water, carbon, energy), and fertilizer use efficiency should be considered. These could also assist in sustainable development.

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Climate Change and Crop Pollination

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Introduction

Observational evidence from all continents shows that many ecosystems are affected by regional and global climate changes, particularly temperature increases (IPCC, 2007). Studies have shown that both the distribution and phenology of many plants and animals are biased in the directions predicted from global warming in the last few decades (Parmesan, 2006), indicated by a global advancement of spring events by 2.3 days per decade and a species range shift of 6.1 km per decade towards the poles (Parmesan and Yohe, 2003). For organism groups involved in pollination interactions, this is evident through recent changes in flowering phenology, e.g., onset of flowering (Sparks *et al*., 2000; Fitter and Fitter, 2002; Miller-Rushing *et al*., 2006) and the first-appearance dates of butterflies and migrating birds (Roy and Sparks, 2000; Gordo and Sanz, 2005, 2006). Whether climate warming will affect ecosystem functioning depends on how interactions among species are influenced.

One of the most important ecosystem services for sustainable crop production is the mutualistic interaction between plants and animals. Pollination interactions are important as they benefit both biodiversity and humans. A great diversity of plants and animals – mainly insects, birds, lizards and mammals- depend mutually on each other for pollination and food, and their interactions may influence population persistence.

The international community has acknowledged the importance of a diversity of insect pollinators to support the increased demand for food brought about by predicted population increases. Insect pollination is threatened by several environmental and anthropogenic factors, and concern has been raised over a looming potential pollination crisis. The Intergovernmental Panel on Climate Change (IPCC) reports an approximate temperature increase ranging from 1.1-6.4°C by the end of this century. Climate change will exert considerable impacts on global ecosystems. Pollination is a crucial stage in the reproduction of most flowering plants, and pollinating animals are essential for transferring

genes within and among populations of wild plant species (Kearns *et al.*, 1998). Klein *et al.* (2007) found that fruit, vegetable or seed production from 87 of the world's leading food crops depend upon animal pollination, representing 35 percent of global food production. Roubik (1995), provided a detailed list for 1330 tropical plant species, showing that for approximately 70 percent of tropical crops, at least one variety is improved by animal pollination. The total economic value of crop pollination worldwide has been estimated at •153 billion annually (Gallai *et al.,* 2009). The leading pollinator-dependent crops are vegetables and fruits, representing about •50 billion each, followed by edible oil crops, stimulants (coffee, cocoa, etc.), nuts and spices (Table 1).

Table 1 Economic impacts of insect pollination of the world agricultural production used directly for human food and listed by the main categories ranked by their rate of vulnerability to pollinator loss

Crop category	Average value of a production unit	Total production economic value (EV)	Insect pollination economic value (IPEV)	Rate of vulnerability (IPEV/EV)
	• per metric tonne	109 •	109 •	%
Stimulant crops	1225	19	7.0	39.0
Nuts	1269	13	4.2	31.0
Fruits	452	219	50.6	23.1
Edible oil crops	385	240	39.0	16.3
Vegetables	468	418	50.9	12.2
Pulse	515	24	1.0	4.3
Spices	1003	7	0.2	2.7
Cereals	139	312	0.0	0.0
Sugar crops	177	268	0.0	0.0
Roots and tubers	137	98	0.0	0.0
All categories		1 618	152.9	9.5

Source: Gallai *et al*., 2009.

The area covered by pollinator-dependent crops has increased by more than 300 percent during the past 50 years (Aizen *et al.,* 2008; Aizen and Harder, 2009). A rapidly increasing human population will reduce the amount of natural habitats through an increasing demand for food-producing areas, urbanization and other land-use practices, putting pressure on the ecosystem services delivered by wild pollinators. At the same time, the demand for pollination in agricultural production will increase in order to sustain food production.

Climate warming and pollinators

Most pollinators are insects and, because insects are small and poikilothermic, it is likely that temperature will be critical for their life cycle development and activity patterns, which is particularly evident in alpine and arctic regions (Totland, 1994; Hodkinson *et al*., 1998). Plant-pollinator interactions can be disrupted in at least two ways: through temporal (phenological) and spatial (distributional) mismatches that may change the availability of mutualistic partners. Mismatch occurs when the original mutualistic partners experience reduced sharing of habitat either in time or space, leading to a partial or complete trophic decoupling (Stenseth and Mysterud, 2002; Visser and Both, 2005). It may affect plants by reduced insect foraging and pollen deposition, while pollinators experience reduced food availability. Memmott *et al*. (2007), simulated how global warming might affect a highly resolved plant pollinator network.

Climate change may be a further threat to pollination services (Memmott *et al.*, 2007; Schweiger *et al*., 2010; Hegland *et al.*, 2009). Indeed, several researchers (van der Putten *et al.*, 2004; Sutherst *et al.*, 2007) have argued that including species interactions when analyzing the ecological effects of climate change is of utmost importance. Empirical studies explicitly focusing on the effects of climate change on wild plant-pollinator interactions are scarce and those on crop pollination practically non-existent.

Consequences of mismatches

Synchronized timing of mutualistic partners may be important for efficient pollination of plants and survival of pollinators. Therefore, one of the major concerns related to global warming and pollination interactions is the demographic consequence of mismatches between plants and pollinators. If mismatches are to seriously affect pollinator demography, then pollinator population densities and distributions must be controlled by bottom-up forces (Durant *et al*., 2007), such as flower abundance. Likewise, whether mismatches will significantly influence plant demography depends on the extent to which plants are top-down controlled through effects of pollinator abundance on pollen availability and mobility (Elzinga *et al.,* 2007). In plants, a mismatch with important pollinators could reduce pollen deposition through altered visitation (quantity or quality of floral visits), potentially increasing pollen limitation. Among plant species, limitation of reproduction due to insufficient pollination is common (Ashman *et al*., 2004). However, the impact of pollen limitation (i.e., a top-down force) on population dynamics, and its relative importance compared to resource limitation (i.e., bottom-up forces), is still poorly understood, although a few studies have shown that increased seed set or seed mass after supplemental pollination can positively influence recruitment, survival and population growth rates of flowering plants (Hegland and Totland, 2007; Price *et al*., 2008). Another consequence of mismatches is the cascading effects they might have on species interactions occurring later in the season. A crash in early-emerging pollinator populations may affect both early and later flowering species and sequentially flowering species may facilitate each other through maintenance of pollinator populations (Waser and Real, 1979).

Climate change

Estimates from the IPCC indicate that average global surface temperatures will further increase by between 1.1°C (low emission scenario) and 6.4 °C (high emission scenario) during the 21st century, and that the increases in temperature will be greatest at higher latitudes (IPCC, 2007). The biological impacts of rising temperatures depend upon the physiological sensitivity of organisms to temperature change. Deutsch *et al.* (2008) found that an expected future temperature increase in the tropics, although relatively small in magnitude, is likely to have more deleterious consequences than changes at higher latitudes. The reason for this is that tropical insects are relatively sensitive to temperature changes (with a narrow span of suitable temperature) and that they are currently living in an environment very close to their optimal temperature. In contrast Deutsch *et al.* (2008), pointed out that, insect species at higher latitudes – where the temperature increase is expected to be higher – have broader thermal tolerance. Warming may actually enhance the performance of insects living at these latitudes. It is therefore likely that tropical agro ecosystems will suffer from greater population decrease and extinction of native pollinators than agro ecosystems at higher latitudes.

Currently, farmers manage only 11 of the 20, 000 to 30, 000 bee species worldwide with the European honey bee (*Apis mellifera)* being the most important species. Dependance on only a few pollinator species belonging to the *Apis* genus has been shown to be quite risky. *Apis*-specific parasites and pathogens have lead to massive declines in honey bee numbers. Biotic stress accompanied with climate change may cause further population declines and lead farmers and researchers to look for alternative pollinators.

Some crop plants are more vulnerable to reductions in pollinator availability than others. Ghazoul (2005), defined vulnerable plant species as:

- having a self-incompatible breeding system, which makes them dependent on pollinator visitation for seed production;
- being pollinator-limited rather than resource-limited plants, as is the case for most intensively grown crop plants, which are fertilized; and
- being dependent on one or a few pollinator species, which makes them particularly sensitive to decreases in the abundance of these pollinators.

Sensitivity entomophilous crop to elevated temperatures and drought

Plant development is mainly determined by mean temperature and photoperiod. Extreme temperatures and drought are short-term events that will likely affect crops, particularly during anthesis (Wheeler *et al.,* 1999). While it is clear that drought and water stress will negatively affect crop growth and yield, their impacts on pollination functions are less well understood. Most of the work carried out on the impacts of drought on crop yield is from research on non pollinator dependent crops such as grain crops or wild plants. Akhalkatsi and Losch (2005), found reductions in inflorescence and flower numbers in the annual garden spice legume *Trigonella coerulea* when subjected to controlled drought conditions. Flowers with fewer attractants are less attractive to pollinators (Galloway *et al.,* 2002;; Mitchell *et al.,* 2004) and will experience reductions in pollination levels, with decreased seed quality and quantity (Philipp and Hansen, 2000; Kudo and Harder, 2005). Crop species experiencing drought stress may also produce lower seed weight and seed number, resulting in reduced yield (Akhalkatsi and Losch, 2005). Yield reduction under drought may also result from a decrease in pollen viability along with an increase in seed abortion rates, which have been identified as the most important factors affecting seed set (Melser and Klinkhamer, 2001).

Pollinator activity

There are several ways of assessing the status of pollinator species and communities, and the structure of pollination networks (Committee on the Status of Pollinators in North America, 2007). Two effective methods have been identified to estimate bee species richness: pan traps and transect walks (Westphal *et al.,* 2008). Pan traps passively collect all insects attracted to them without assessing their floral associations or whether they pollinate crop species. They can, however, be an effective method for estimating relative population size and species richness as they collect a large number of individuals with little effort. The effectiveness of pan traps in collecting other types of pollinators such as butterflies and hoverflies has not been assessed to the same extent as for bees.

Since pollination depends upon the number of visits provided by each pollinator as well as the pollinator's effectiveness in transporting pollen from anthers to stigmas, pan traps are an inferior method in pollination studies. The visitation frequency of pollinators can be measured by observing and counting pollinators foraging on flowers. Transect walks, which can be used to capture insects visiting crop flowers, are in some ways a better method than pan traps, although more laborious (Westphal *et al.,* 2008; Vaissiere *et al.,* 2011).

Vegetation surrounding fields of entomophilous crops must be conserved and managed to maintain wild pollinators within agricultural landscapes. It is particularly important to conserve additional food resources for the periods when the crops are not flowering. In agroecosystems depending on wild pollinators, pollinator diversity and the structure of pollination networks – including wild flowering plants outside agricultural fields have shown to buffer against the negative effects of perturbations. Ecosystems with high species diversity are more resilient to disturbance than less diverse systems. With respect to crop pollination, several studies have indicated that agricultural fields in close proximity to natural habitats may benefit from pollination of native pollinators (Klein *et al.,* 2003). Ricketts *et al.* (2004) found that pollination by a diverse group of wild bees enhanced coffee production as several bee species compensated for a drop in honey bee visitation in certain years.

Climate variables

The most relevant climate variables may vary among crop and pollinator species, and among different climate regions.

Table 2 Habitat requirements and taxonomic groups of the different nesting guilds of pollinators

Nesting pollinator guilds	Nesting Habitats	Taxonomic groups
Miners	Open habitats, Excavate holes in the ground	Andrenidae, Melittidae, Oxaeidae and Fideliidae. Most of the Halictidae, Colletidae and Anthophoridae.
Masons	Pre-existing cavities, pithy or hollow plant stems, small rock cavities, abandoned insect burrows or even snail shells	Two genera within Apidae (Xylocopa and Ceratina) and one within Megachilidae (Lithurgus)
Carpenters	Woody substrate	Two genera within Apidae (Xylocopa and Ceratina) and one within Megachilidae (Lithurgus)
Social nesters	Pre-existing cavities	Apidae: honey bees, bumblebees and stingless bees

Temperature

Pollinators and plants have different climatic requirements, and may therefore, respond differently to changes in ambient temperature. Temperature can induce different responses in plants and pollinators. For example, increased spring temperatures may postpone plant flowering time while pollinators might be unaffected. Even if plants and pollinators respond to the same temperature cue, the strength of the response might differ (Hegland *et al.,* 2009). Data on the number of degree days, or maximum temperature during the day or hours with temperature above or below a certain threshold may be more important for crop plants and pollinators than temperature during observations of pollinator activity. Tropical pollinators may respond to different temperature cues than pollinator species at higher latitudes. Temperature-induced activity patterns may also differ depending on pollinator size, age and sex.

Precipitation

High precipitation may limit pollinators' foraging activity. Optimal foraging conditions for pollinators are sunny days with low wind speed and intermediate temperature. Climate change is expected to alter existing precipitation patterns. Some areas will likely experience decreased rainfall, leading to more extensive drought periods. This water stress may decrease flower numbers and nectar production. Snow cover might also be reduced with increased temperatures. Indeed, bumblebees have been shown to respond more to snow cover than to temperature (Inouye, 2008).

Extreme climate events

Extreme climate events might have detrimental effects on both crop plants and pollinator populations. High temperatures, long periods of heavy rain and late frost may affect pollinator activity either by reducing population sizes or by affecting insect activity patterns. The probability of extreme climate events may change in the future. Risk assessments should be conducted to better understand the changes in frequency of extreme climate events and minimize the effects.

Other threats to pollination services

Pollination is under threat from several environmental pressures. Climate change is only one, and it cannot be seen in isolation, but should be addressed in relation to other pressures affecting plant-pollinator interactions. Here we list some of the most important pressures to be assessed in order to understand how crop pollination might be affected by climate change.

i) Agricultural practices

Agricultural intensification by covering large areas with monocultures increases agroecosystems' vulnerability to climate change. Adaptation strategies at the farm level can include increased farm diversity, including crop diversity, and changes in sowing date, crops or cultivars. Greater crop diversity can decrease crops' vulnerability to climate variability, as different crops respond differently to a changing climate. Regional farm diversity may also buffer against the negative effects of climate change at a large scale as it entails a large variability in farm intensity and farm size (Reidsma and Ewert, 2008).

ii) Invasive species

Invasive species may benefit from climatic changes and proliferate in their new habitats. Climate change is predicted to increase invasion of alien species, especially in northern regions. However, the effects of climate change on invasive species and pollination interactions may vary depending on the species and ecosystem in focus (Schweiger *et al.,* 2010). It is necessary to assess the controllability of invaders in order to assist policy makers in ranking threats from different invasive species for more effective use of limited resources (Ceddia *et al.,* 2009).

iii) Pest species, pesticides and pathogens

Some invasive insect and plant species are pest organisms, which may cause severe damage to agricultural production. It is expected that climate change will affect various types of pests in different ways (Garrett *et al.,* 2006; Ghini and Morandi, 2006). Increased temperatures may speed up pathogen growth rates. Warming may also favor weeds in comparison to crops and increase the abundance, growth rate and geographic range of many crop-attacking insect pests (Cerri *et al.,* 2007). Increased demand for control of plant pests often involves the use of pesticides, which can have negative impacts on human health and the environment (Damalas, 2009), including ecosystem services such as pollination. Diffenbaugh *et al.* (2008) assessed the potential future ranges of pest species by using empirically generated estimates of pest overwintering thresholds and degree-day requirements along with climate change projections from climate models. Pollinators are also negatively affected by predators, parasites and pathogens. Natural movements of pollinator species and exchanges of domesticated bees among beekeepers will bring them in contact with new pathogens. Pests and pathogens may find new potential hosts. It is therefore important to conserve the genetic variability among and within important pollinator species (including races and varieties) to decrease disease-mediated mortality. Managed pollinators may need veterinary aid and appropriate control methods to prevent catastrophic losses (Le Conte and Navajas, 2008).

The economic value of crop pollination

Information on visitation frequency and subsequent seed set is valuable when categorizing crops according to their degree of dependence on crop pollination (Delaplane and Mayer, 2000). However, the total value of pollinators' ecosystem services at both local and larger scales is little understood. A protocol for assessing pollination deficits in crops has been developed by FAO in collaboration with other institutions (Vaissiere *et al.,* 2011). Experiments carried out using such protocols will identify crop species under threat of pollination failure in different regions. Further research focused on vulnerable species can identify actions to minimize negative effects. A recent report published by FAO can be used as a tool for assessing the value of pollination services at a national or larger scale, and vulnerabilities to pollinator declines (Gallai *et al*., 2009).

Conclusion

Although concern has been raised about negative effects of climate change on the services provided by pollinating insects, there is still paucity of scientific literature regarding how pollination interactions may be affected. The scientific literature provides numerous examples of climate-driven changes in species distribution and several bioclimatic models have been developed. However, when it comes to research on species interactions – especially interactions between pollinators and crop plants, which account for 35 percent of global food production – there is still a lack of information.

Climate change may affect the phenology and distribution ranges of both crop plants and their most important pollinators, leading to temporal and spatial mismatches. It is therefore, important to identify the temperature sensitivity of the most important pollinators and their crop plants, and the environmental cues controlling the phenology and distribution of the identified species. Long-term monitoring of agro ecosystems and experimental assessments of species' climate sensitivity may enhance our understanding of the impacts of climate change on crop pollination. The current knowledge of the potential ecological consequences of increasing temperatures is limited and often must be deduced from indirect evidence or basic ecological knowledge of pollination interactions or studies of the mutualistic partners separately. Timing of both plant flowering and pollinator activity appears to be strongly affected by temperature, and their response appears to be linear within the limits of temperature fluctuation observed during recent decades. Thus, plant and pollinator responses to climate warming may act in concert, although there may be considerable variation in the thermal sensitivity across species

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Conservation Agriculture for Natural Resource Management and Mitigating Changing Climate Effects

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Introduction

Conservation agriculture, for most of the people, means minimum tillage *viz*., no-tillage, reduced tillage, strip tillage, etc. which leaves sufficient residues at the soil surface. This meaning is in fact misleading as reduced tillage and residue retention aim just to sustain/ improve soil structure and perhaps conserve soil moisture through reduced tillage. The umbrella of conservation has to cover not only conservation of soil structure and moisture but also to ensure higher input water productivity, increased soil organic carbon (SOC), better soil temperature conditions apart from conservation of environment with sustained/improved agricultural production. It can also be referred to as resource efficient or resource effective agriculture. For example, improving input water productivity could be conservation irrigation; improving soil structural stability could be soil conservation; reducing tillage for higher infiltration and lower runoff could be conservation tillage; in-situ and ex-situ harvesting of rainwater could be water conservation; mitigating the environmental degradation could mean environment conservation. All these aspects thus are covered under the umbrella of Conservation Agriculture. In other words, in conservation agriculture, an integrated approach of improving SOC, input water productivity, harvesting excess rainwater needs to be followed for mitigating the negative impacts of changing climatic conditions.

The technologies which help in achieving the aims of conservation agriculture are termed as “resource conservation technologies (RCTs)” and efforts are being made globally to develop and refine these technologies for the specific soil and climatic conditions. These technologies are targeted at increasing the agricultural productivity, sustaining/improving soil health through reducing and reversing soil degradation, reducing air pollution, and increasing nutrient, labour and water-use efficiencies. Examples of these technologies include laser leveling, reduced and zero tillage, direct seeding of rice, raised beds, retention of crop residues, balanced and integrated fertilization, and need-based irrigation. Some of these technologies deal with improving irrigation productivity (conservation irrigation), while others deal with improving soil health and environment (SOC sequestration). However, both these strategies aim at managing natural resources as well as the environment. This chapterdeals with the technologies related to conservation irrigation and SOC sequestration with an aim at reducing the input water use and increasing SOC.

Conservation irrigation in rice and wheat

Approaches to save irrigation water can be quite different for rice and wheat, and strategies for saving irrigation water in one crop may impact positively or negatively on yield and water productivity of the following crop, and hence total cropping system. The generic approaches to saving water or increasing irrigation water productivity *viz*., laser land leveling, drainage recycling etc. can benefit both rice and wheat at the field scale. While some water saving technologies decrease drainage losses without affecting evaporation, others predominantly affect both. Reduction in evaporation is likely to be true water saving, whereas drainage can often be recaptured at some scale in the system. The technologies which help in saving irrigation water or simply saving the energy for pumping out water for rice and wheat are better known as "conservation irrigation technologies". Some of these techniques are being discussed as under.

Raised bed planting of rice

The accumulated irrigation water applied in puddled flats with different irrigation regimes *viz*., continuous flooding throughout (PTR-CF) and intermittent irrigation at an interval of 2 days after continuous submergence for first 15 days (PTR-2d) and in raised beds with intermittent irrigation at 2 days after daily irrigation for the first 15 days (RB-2d) is shown in Fig 1. The amount of irrigation water used in sandy loam till first 15 days after transplantation (DAT) is similar in beds and flats. However, the total amount of irrigation water used in case of puddled flats with 2-d interval did not differ much from that used in raised beds with similar irrigation interval. In loam, the amount of irrigation water used in RB-2d was higher from that in puddled flats with both the irrigation regimes. The total amount of irrigation water applied to raised beds remained higher than that applied to puddled flats with 2-d irrigation regime. It is worth mentioning here that the furrows were applied irrigation water filled to the brim, whereas in PTR-CF, 5 cm of water head was maintained throughout and in PTR-2d, the depth of eachirrigation was 7.5 cm.

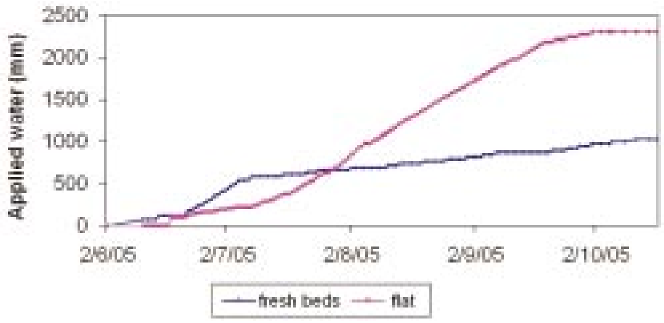

Fig 1 Accumulated amount of applied irrigation water in beds and puddled flats

The results of differential irrigation regimes on beds (Table 1) during 2004 show that both grain and straw yields were maximum on beds with half-furrow depth irrigation water at 2 d interval (RB-H2d). The grain yield was 18% higher in RB-H2d than that in RB-F2d and consumed 30% lower irrigation water. Increasing the frequency of irrigation (RB-H1d) with half furrow-depth decreased the grain yield by 5% from that with RB-H-2d and consumed 18% higher irrigation water. The beds being an unpuddled system, the applied irrigation water immediately moves down out of the root zone after wetting the soil under beds, due to higher infiltration and percolation rates (Kukal *et al*., 2005a). This may increase the leaching losses of nitrogen out of the root zone. Thus reducing the amount of irrigation water per irrigation might have helped to decrease the N leaching losses and hence increase the grain yield of rice.

Table 1 The biomass, rice grain yield and irrigation water applied to rice on beds in relation to differential irrigation during 2004

Treatments Productivity	Straw yield ($t\ ha^{-1}$)	Grain yield ($t\ ha^{-1}$)	Irrigation water (mm)	Water ($kg\ m^{-3}$)
PTR-2d	9.09	7.23	1555	0.46
RB-F2d	9.15	5.55	1480	0.37
RB-H2d	10.3	6.55	1020	0.64
RB-H1d	11.0	6.22	1240	0.50

F2d means full furrow depth of irrigation water at 2 d interval, H2d means half furrow depth of irrigation water at 2 d interval and H1d means half furrow depth of irrigation water at 1 d interval

This practice of irrigation application was then evaluated on raised beds at farmers' field scale during 2005 (Table 2), where the irrigation was applied on the basis of soil matric potential of -15 kPa at 20 cm soil depth from the surface of the bed (RB-H-SMP) instead of 2 d irrigation interval. The water productivity of rice was highest on beds (0.70 kg m^{-3}) when compared with that in RB-F2d (0.20 kg m^{-3}) and puddled flats with farmer's practice of irrigation (PTR-farmer) (0.34 kgm^{-3}) where they keep the fields continuously submerged and thereafter irrigate once a week. It resulted in reduction of irrigation water use to the extent of 46% from that used with farmers' practice and even higher (53%) from that in RB-F2d. It could be concluded that the amount of irrigation water use in raised beds can be reduced from that used in puddled flats only by reducing the amount of irrigation per irrigation and this helps in increasing the rice grain yields on raised beds.

Wheat on raised beds

Grain yields were observed to be higher on fresh and permanent beds than on flat layouts on both the soils, except lower grain yield on permanent beds, which had direct seeded rice on beds on sandy loam. Grain yield of wheat on conventionally tilled plots was on a par with direct drilled wheat on both the soils. Straw yield was higher on the loam than at the sandy loam. The straw yield tended to be higher on flats than on beds though the differences were non-significant on both the soils. The straw yield was significantly higher in CTW than in DDW on sandy loam. However, there were no significant differences among treatments on loam.

Table 2 The performance of rice and irrigation water applied with differential irrigation during 2005

Treatmentswater productivity	Irrigation (mm)	Water (kgm^{-3})	Yield ($t\ ha^{-1}$)	HI
PTR-2d	1452	0.49	7.1	0.61
RB-H-SMP	1026	0.70	7.2	0.88

H-SMP means half furrow depth of irrigation water on the basis of soil matric potential of 15 kPa at 15-20 cm depth, F2d means full furrow depth of irrigation water applied at 2 days interval

Soil matric potential based irrigation scheduling to rice

The continuous flooding regime (followed by the farmers since a long time) is no more relevant. It has been shown that intermittent irrigation after 1, 2 or 3 days does not affect rice grain yield. For Punjab soils, irrigation at 2 days after complete disappearance of irrigation water does not affect the rice yields. However, the water requirement of rice field is a function mainly of climate and soil type. Thus, both the climatic demand of the atmosphere and the ability of the soil to supply sufficient moisture determine the water requirement of the crop. The similar amount of water in coarse and fine textured soils may not be available to the crop plants due the differential force of attraction of water molecules to the soil matrix called soil matric potential. Thus soil matric potential is better criterion for scheduling irrigation to rice crops. Studies (Kukal*et al.*, 2005a) have shown that rice crop if irrigated on the basis of soil matric potential of -16 kPa at 15-20 cm soil depth can result in saving of about 30% of irrigation water without any adverse effect on rice yield (Table 3).

Table 3 Soil matric potential-based irrigation scheduling to rice

Treatments	Grain yield (t/ha)	Irrigation Water (cm)
80 ± 20 cm	6.64	127
120 ± 20	6.44	112
160 ± 20	6.40	102
200 ± 20	6.21	89
240 ± 20	5.99	74
Recommended	6.43	148

Source: Kukal *et al.* (2005a)

Irrigation water applied in furrows when rice is grown on raised beds has been reported to save about 25-30% of irrigation water in comparison to intermittent irrigation at 2 d interval. However, the irrigation water needs to be applied upto half furrow depth to avoid unnecessary losses of water from the unpuddled furrows.

Direct dry-seeded rice

The interaction effect between establishment method and irrigation schedule on grain yield was significant. Grain yield of PTR and DSR with daily and 20kPa irrigation was similar and significantly higher than the yield of all other treatments each year (Fig 2). Grain yield was significantly higher in PTR irrigated at 40 and 70 kPa than in DSR 40 and 70 kPa, respectively. The higher yields of DSR and PTR with daily and 20 kPa irrigation were largely due to higher panicle density and more florets per panicle, and to a lesser degree to higher grain weight (Yadav *et al*., 2011a). The lower yields of DSR than PTR at 40 and 70 kPa were mainly due to lower panicle density, and to smaller degree to fewer florets per panicle and lower grain weight.

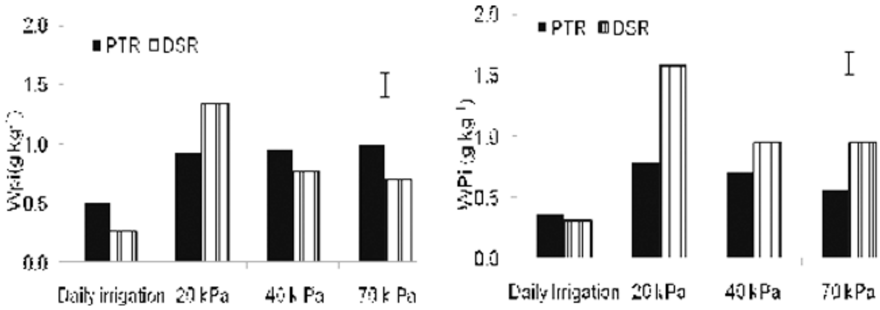

Fig2 Irrigation water productivity of direct dry-seeded rice during 2008 and 2009

Input water productivity (WP_{I+R}) was much lower than WPI in the respective treatments each year due to large amount of rain each year, and it ranged from 0.22 to 0.58 gkg^{-1}in 2008 and from 0.22 to 0.63 g kg^{-1} in 2009. The trends in WP_{I+R} were similar to those in WPI. There was a significant interaction effect between establishment method and irrigation schedule on WPI+R each year. Water productivity with respect to ET ranged from 0.58 to 1.24 and 0.61 to 1.14 g kg^{-1} in 2008 and 2009, respectively. There was no effect of establishment method nor interaction between establishment and irrigation treatments on WPET in 2008; however, the interaction was significant in 2009. Each year, WPET was significantly higher when irrigation was scheduled at 20 kPa (approximately 1.2 gkg^{-1}) than in all other irrigation schedules. This was due to similar yield and lower ET in comparison to daily irrigation, and to higher yield than in the 40 and 70 kPa treatments, which more than compensated for the reduction in ET in the latter treatments. However, WPET was similar in PTR and DSR within daily and 20 kPa treatments, respectively, and significantly higher in PTR than in DSR at 40 and 70 kPa due to higher yield.

Tillage and mulching in relation to soil and water management

Soil-conserving practices that enhance and maintain favourable soil structure include mulch farming and conservation tillage methods. Mulching with crop residues provides an effective method of reducing water and associated nutrient losses. Studies conducted in the foothills of Shiwaliks region (most fragile region of Himalayan Ecosystem) showed that with the application of 4 t ha^{-1} straw mulch, the runoff decreased by 56.7% and soil loss by 71.7%. Also the concentration of both total N and available P in the sediment fraction of surface runoff decreased by 60% in mulched than in unmulched plots. Usefulness of strawmulching for conservation of moisture in the soil profilehas been well established in the region. Even the locally available mulch material other than straw can be used. Mulching @ 4 tha^{-1} with locally available wild shrub *Adhatoda vasica* (basooti) in the standing maize crop during the first week of August significantly increased maize yield over no mulch treatment. The reduction in both runoff and soil loss was also influenced by rainfall intensity. At a rainfall intensity of 24 mm h^{-1}, the reduction in soil loss was 41, 70, 90 and 94% under straw mulch application @ 2, 4, 6 and 8 t ha^{-1}, respectively. On a sandy loam soil (Table 4), the increase in rainfall intensity from 10 to 80 mmh^{-1} increased runoff from 14.3 to 88.2% in unmulched and 4.5 to 64.4% in mulched plots on a field with 1% slope.

Table 4 Effect of mulch on grain yield of maize and water use

Parameter	Fallow-wheat		Maize-wheat	
	Un-mulched	Mulched	Un-mulched	Mulched
Residual moisture (cm per 180 cm profile)	357	367	336	343
Water use (cm)	305	297	248	259
Grain yield (t ha^{-1})	3.7	3.7	2.6	3.1
WUE (kg per ha cm)	122	125	105	122

To economize the use of available mulch materials and reduce the hazards of insects and pests, studies on the modes of mulch application and their effect on runoff and soil loss have recently started receiving attention in the region. In a study conducted in the region (Table 5), it was observed that the mode of mulch application has more pronounced effect on sediment reduction than that on runoff. The application of mulch in the form of band placement was found superior to covering the lower one-third portion of the field.

The erosion control effectiveness of tillage depends on the amount of crop residue applied and the degree of surface roughness exhibited by the soil. The field studies conducted in the foothills of Shiwaliks showed that tillage increased infiltration and decreased runoff, thereby conserving more moisture in the soil. Deep tillage significantly decreased runoff and soil loss and increased water intake compared to shallow tilled and untilled plots. Deep tillage, however, is not an acceptable practice in the region due to lack of special equipment's, tractors and overall small sized fields (Table 6). Tillage on the other hand results in crusting of soil surface, which apart from hampering germination, increases runoff by decreasing infiltration rate of soils. Effectiveness of tillage in decreasing runoff was greatly enhanced in the presence of mulch. The application of mulch @ 6 tha^{-1} decreased soil losses by 81.5 and 84.9% than those in without mulch under large and small clod sizes, respectively. Also mulch and tillage interacted significantly in decreasing the amounts of P and K in the sediment portion and soluble N and P in the water portion.

Table 5 Effect of rate and mode of mulch application on runoff in a sandy loam soil

Mulch rate (t ha^{-1})	Mode of mulch application	Runoff (mm)	
		Cropped	Uncropped
0	-	76	87
3	Band placement	54	63
	Lower 1/3 covered	43	54
6	Band placement	41	49
	Lower 1/3 covered	37	44
	Whole plot covered	26	36

Table 6 Effect of deep tillage and mulching on runoff and intake rate of sandy loam soil

Parameter	No mulch		Mulched	
	Shallow-tilled	Deep- tilled	Shallow-tilled	Deep- tilled
Seasonal runoff (mm)	123	112	73	69
Water intake (mm h^{-1})	9.9	11.5	13.4	13.6

Thus, in addition to their role in effectively checking both the soil loss and runoff, application of mulch materials was found to be quite effective in conserving soil moisture and increasing crop yields.

Soil physical environment

Land use

Land use has a great effect on soil physical environment. Saha *et al*. (2012) observed that in the 0-15 cm soil layer, the WSA>2 mm (macroaggregates) were highest (17.3%) in grasslands followed by forest (7.38%), agricultural (4.08%), and lowest (0.85%) in eroded lands. The micro-aggregates (WSA<0.25 mm) were highest (25%) in eroded and lowest in forest soils (3.39%). The eroded soils had 2.17, 7.37 and 3.42 times higher amount of microaggregates (WSA<0.25 mm) than agricultural, forest and grassland soils, respectively. Cultivation of forest and grassland leads to 3.4 and 1.5 times increase in the proportion of microaggregates, respectively. The MWD of aggregates in surface soil (0-15 cm) followed a similar trend as the water stable macroaggregates (WSA>2 mm) (Table 7). The SOC in the surface soils was highest in grassland soils (13.2 g kg^{-1}) and lowest in eroded soils (1.95 g kg^{-1}) though SOC of 15-30 cm soil layer was significantly higher in forest soils than in grassland soils (Table 7).

Table 7 Aggregate size distribution, MWD and SOC in relation to land use

Land use	% Water stable aggregates (WSA)		MWD(mm)	SOC (g kg^{-1})
	>2mm	<0.25 mm		
0-15 cm soil layer				
Eroded	0.85a	25.0a	0.19a	1.95a
Agricultural	4.08b	11.5b	0.36b	7.23b
Forest	7.38c	3.39c	0.60c	9.60c
Grassland	17.3d	7.30d	1.13d	13.2d
15-30 cm soil layer				
Eroded	4.38a	19.0a	0.28a	2.50a
Agricultural	2.33b	11.1b	0.31a	4.80b
Forest	6.91c	5.51c	0.52b	7.01c
Grassland	7.40c	9.52d	0.50b	5.12d

MWD-mean weight diameter; SOC- soil organic carbon

The water drop stability (WDS), as determined by the single raindrop technique, differed significantly among different land uses (Saha *et al*., 2012). In the surface (0-15 cm) soil layer, the aggregates from grassland soils recorded the highest WDS (628 drops g^{-1} soil), followed by forest (570 drops g^{-1} soil) and agricultural soils (418 drops g^{-1}soil). It was 61% lower in the eroded soils than in grassland soils. The bulk density of both individual aggregates and bulk soil was highest in eroded soils. It decreased by 4.3 and 6.1% in agricultural, 8.6 and 6.7% in forest and 11.6 and 8% in grassland soils from that in eroded surface soils. The bulk density of individual aggregates from eroded land was highest (1.73 Mg m^{-3}), followed by agricultural (1.68 Mg m^{-3}), forest (1.58 Mg m^{-3}) and grassland (1.53 Mg m^{-3}) soils, in comparison to the corresponding values of 1.63, 1.53, 1.52 and 1.50 Mg m^{-3}, respectively for bulk soil. The total porosity of aggregates was significantly higher in grassland soils (42.1%), followed by forest (40.7%), agricultural (36.3%) and eroded soils (34.5%). Cultivation of the natural grassland and forest soils could cause 13.8 and 10.8% decrease in total porosity. The extent of macropores in the surface layer of eroded and agricultural soils was found to be similar but significantly lower than in forest and grassland soils. Similar was the trend of transmission and storage pores except that the proportion of transmission pores were lower by 60-70% compared to the macropores. The macropores constituted 10-13% total soil volume whereas, the transmission pores varied from 4.0-5.5%. The storage and residual pores constituted 8.7-11.3% and 8.5-13% of the total soil volume. The field capacity (FC) moisture content in the surface soil layer was highest in grassland soils closely followed by forest soils but was sufficiently lower in agricultural and eroded soils. The differences in moisture retention, however, decreased with increase in soil matric suction. The SOC could explain 79% variation in plant available water (PAW). However, the role of SOC in increasing soil moisture content at a particular suction was more pronounced (R^2=0.76-0.81) at lower (0-33 kPa) suction levels than at higher suction levels (500-1500 kPa).The saturated hydraulic conductivity (K_{sat}) of forest and grassland soils was similar in both surface and subsurface layers. It decreased to 3.9 cm h^{-1} in agricultural soils and 1.56 cm h^{-1} in eroded soils. Even in the subsurface soil layers, the K_{sat} was sufficiently higher in forest and grassland soils (2.93-3.85 cm h^{-1}) compared to eroded soils (1.98 cm h^{-1}). The decrease in K_{sat} with soil depth was much more pronounced in the agricultural soils.

Balanced and integrated fertilization

The balanced inorganic fertilization has been reported to improve soil physical environment. The soil bulk density profiles (0-60 cm) recorded at the harvest of both maize and wheat (Rasool *et al*., 2008) revealed that FYM decreased soil bulk density significantly in comparison to that in control plots in all the layers. However, the decrease was more in upper soil layers (0-15 and 15-30 cm) than in the lower layers (30-45 and 45-60 cm). Balanced use of inorganic fertilizers ($N_{100}P_{50}K_{50}$) significantly decreased bulk density of all the soil layers from that in control, both after maize and wheat crops. The bulk density of FYM and $N_{100}P_{50}K_{50}$plots was not significantly different from each other.The mean total porosity of soil increased significantly with the application of FYM and $N_{100}P_{50}K_{50}$ in both maize and wheat crops. The FYM promotes total porosity of the soil as the microbial decomposition products of organic manures such as polysaccharides and bacterial gums are known to act as soil particle binding agents. These binding agents decrease the bulk density of the soil by improving soil aggregation and hence increase the porosity. Total porosity increased with the application of balanced fertilizers in both maize and wheat. The higher total porosity of the soil particularly of the surface layer helps in ready exchange of O_2 and CO_2 between the soil and the atmosphere, thereby, promoting better root growth in the soil. The wet stability of aggregates, expressed in terms of mean weight diameter (MWD), was highest in the FYM-treated plots both at the harvest of maize (0.160 mm) and wheat (0.172 mm), followed by that in $N_{100}P_{50}K_{50}$ treatments. The FYM improved the MWD by 65 and 74% at the end of maize and wheat crops, whereas $N_{100}P_{50}K_{50}$ increased the MWD by 55 and 61%, respectively, from that in control plots. The average water holding capacity (WHC) of soil during maize was (21%) higher in FYM plots than in control plots, whereas it was 11% higher in $N_{100}P_{50}K_{50}$ plots. The WHC of unbalanced fertilizer plots (N_{100}) was not significantly different from that in control plots.

Soil organic carbon sequestration

Land use

The soil organic carbon (SOC) is good indicator of soil quality and environmental stability. Among the factors affecting SOC pool and fluxes in a watershed, land use changes and soil erosion are of importance. A study was conducted in TypicUstochrepts of Northwest India to understand the impact of forest, grassland, agricultural and eroded lands on aggregate stability and SOC fractions. The stability of aggregate as mean weight diameter (MWD) and SI_{SRT} (stability index) was highest in surface soils (0-15 cm) of grasslands followed by forest, agricultural and eroded lands (Saha *et al*., 2011). The WSA >2 mm (water stable aggregates > 2 mm) were highest (17.3%) in grasslands and lowest (0.85%) in eroded lands. The eroded soils had 2.2, 7.4 and 3.4 times higher amount of micro-aggregates (WSA < 0.25 mm) than agricultural, forest and grassland soils, respectively. The SOC significantly decreased by 20% in forest and 44% in agricultural lands from that in grasslands. In subsoil (15-30 cm), the SOC in eroded, agricultural and grasslands was statistically similar. The SOC stock in the subsoil (15-100 cm) was of significance. The grassland soils could store 41 Mg ha^{-1} SOC stock compared to 31 Mg ha^{-1} in the subsurface layer. This difference widened in forestland, where subsoil contained 73.4% of total SOC stock in a 100 cm soil profile. Among all the SOC fractions studied, labile carbon was mostly affected by erosion and was 91.6% lower in eroded lands than that in grasslands. The magnitude of aggregate associated organic carbon decreased with aggregate size in all the land uses. Among the SOC fractions, the aggregate stability under simulated raindrop impact could better be explained ($R^2 = 0.78$) by hot water soluble carbon whereas the water stability of aggregate could better be explained ($R^2 = 0.69$) by particulate organic carbon.

Balanced and integrated fertilization

Sustaining soil organic carbon (SOC) is of primary importance in terms of cycling plant nutrients and improving the soil physical, chemical and biological properties (Rasool *et al*., 2007, 2008). The SOC is an important index of soil quality because of its relationship with crop productivity. A decrease in SOC leads to decrease in soil's structural stability. Also restoration of SOC in arable lands represents a potential sink for atmospheric CO_2. Agricultural utilization of organic materials, including crop residues enhances the SOC level (Kukal *et al*., 2009) which has direct and indirect effect on soil physical health. Balanced fertilization improves the SOC concentration, both in rice-wheat and maize-wheat cropping systems. In the 60 cm soil profile, the total SOC stocks in both the cropping systems were highest in FYM (31.3 and 23.3 Mg ha^{-1} in rice-wheat and maize-wheat) followed by balanced fertilization (29.6 and 21.3 Mg ha^{-1}) and lowest in unfertilized control (21.4 and 18.7 Mg ha^{-1}). The SOC sequestration rate was 3 times higher in rice-wheat than in maize-wheat soils. The soils under rice-wheat sequestered 55% higher SOC in FYM plots and 70% higher in NPK plots than in maize-wheat. These results document the capacity of optimally fertilized rice-wheat system to sequester higher C as compared to maize-wheat system.

The integrated fertilization helps to improve the soils' physical fertility. The soil structure in terms of mean weight diameter has been found to improve in FYM-plots both in rice (0.237 mm) and wheat (0.249 mm) closely followed by that in $N_{120}P_{30}K_{30}$ plots (Rasool *et al*., 2007, 2008). The addition of both FYM and $N_{120}P_{30}K_{30}$ increased the organic carbon by 44 and 37%, respectively in rice fields. The average water holding capacity (WHC) was found to be 16 and 11% higher with FYM and $N_{120}P_{30}K_{30}$ application from that in control plots. The MWD, total porosity and WHC improved with the application of balanced application of fertilizers. This leads to improved grain yield and uptake of N, P and K by both rice and wheat.

The bulk density of different soil layers as observed at the harvest of wheat did not vary in rice-wheat and maize-wheat (Kukal *et al*., 2009) in response to different treatments. However, the aggregation in terms of mean weight diameter (MWD) improved significantly by FYM as well as NPK. The MWD in rice-wheat increased by 75% with FYM in 0-15 cm soil layer, whereas in maize-wheat it increased by 67%. In lower layers, the increase in MWD with FYM was higher (75-77%) in maize-wheat than in rice-wheat (41-62%). The increase in MWD due to NPK was lower than with FYM in both rice-wheat and maize-wheat. However, it was similar in 0-15 cm soil layer in the two cropping systems, but in lower layers it was again higher in maize-wheat than in rice-wheat system. The increase in MWD due to FYM and NPK decreased with soil depth in rice-wheat, but in maize-wheat it was similar in all the depths.

Thus, improvement in soil physical health by integrated and balanced fertilization, in addition to judicious use of irrigation water through resource conservation technologies are keys for sustained agricultural production in the region.

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Conservation Agriculture in Rice Based Cropping Systems: Innovations for Carbon Management and Livelihood

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Introduction

Varietal breakthrough along with development of crop management technologies in post independence India has boosted the production of crops and provided opportunities for enhancing cropping intensity at farm level and food security at national level. But, the ever increasing population pressure and shrinking land resources has proved to be another turning point in agricultural research and development. The demand of food grains in India will be 238.5 and 268.8 million tones, respectively by 2010 and 2020 (Kumar, 1998). In the projected food demand by 2020, the combined share of rice (41.07%) and wheat (33.89%) will be 75.96%, which covers about 85.5% of the irrigated area of the country. This shows that the productivity growth of the rice and wheat (the major food crops of the country) has been mainly attributed to the varietal breakthrough coupled with irrigation development, intensive use of inputs and over exploitation of natural resource base. There is wide spread degradation of natural resource e.g., soil erosion, runoff, nutrient loss, acidity, water logging, decline in soil organic carbon content, ground water depletion and micro nutrient deficiency in country.

In North East India, the farmer's immediate concern is crop yield improvement and enhancement of basic income for their livelihood. The basic social concept of sustainable management of land is based on balance among the different segments of the society as well as a balance between individual and institutional values. Intensive agriculture and excessive use of external inputs led to degradation of soil, water and genetic resources. Wide spread soil erosion, nutrient mining, depleting ground water table and eroding biodiversity are the global concern which are threatening the food security and livelihood opportunities of farmers, especially the poor and underprivileged. Therefore, there is urgent need to reverse the trend of natural resource degradation.

Soil (land) health degradation is a major problem, especially in intensive agriculture. Physical and biological deterioration of land with associated fertility depletion occurs due to poor agronomic management, water-logging, acidification etc. Intensive cultivation along with poor or no addition of manure, residue removal/burning etc. is further aggravating the situation. Crop production is becoming uneconomical due to higher input cost, low responsiveness to inputs, high labour requirement and poor diversification.

Due to growing resource degradation problems worldwide, conservation agriculture (CA) has emerged as an alternative strategy to sustain agricultural production. It is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently promoting the environmental balance. Conservation agriculture is based on enhancing natural biological processes above and below the ground. Intervention such as mechanical soil tillage are reduced to an absolute minimum and use of external inputs such as agrochemicals and nutrients of mineral or organic origin are applied at optimum level and in a way and quantity that doesn't interfere with or disrupt the biological processes.

Therefore, it is essential to incorporate suitable resource conservation technologies (RCTs) in agronomic practices, which are not only economical and helpful for better growth and development but also enable to utilize valuable resources efficiently and conserves them (Ghosh *et al*., 2010; Das *et al*., 2011). Blending of modern technology with indigenous resource conserving technologies would help to achieve such goals with people's participation.

Rice scenario

Rice (*Oryza sativa* L.) is staple food of more than 60 % of the world's population. Rice is the most important crop of India with highest area of 45 million hectares and second to china in production with 95 mt. The average productivity of rice in India has been between 2-3 t/ha which is at satisfactory level considering the global standards with a scope for further improvement. However, the surplus production scenario has no room for complacency as growth rate is only about 1.4 –1.5 %. Considering population growth at about 1.8 %, the demand for rice is going to be about 140 mt by 2025 AD (Subbaiah, 2005).

Area under rice is expected to be reduced to about 40 m ha in the next 15-20 years owing to water shortage and urbanization in India. More than 80 % of fresh water is consumed for agriculture and 50 % of it goes to rice cultivation. Rice consumes about 3000 –5000 litre of water to produce 1 kg of rice. The per capita availability of water sources declined by 40-60 % in many Asian countries between 1955-1990 (Glieck, 1993) and expected to decline by 15-45 % by 2025 compared to 1990 (Guerra *et al.,* 1998). Therefore, rice could face a threat due to water shortage and hence there is need to develop and adopt water saving methods in rice cultivation so that production and productivity levels are elevated despite the looming water crisis.

Rice is also the staple food of people in the North Eastern Region of India. The productivity of rice in the region is only about 1.74 t/ha compared to national average of 2.2 t ha^{-1}. The demand for rice is growing with ever-increasing population. The region is in deficit of about 1.0 million tonne of rice. Therefore, there is need for steady increase in productivity with limited resources like land, water etc.

Off late, technologies like System of Rice Intensification (SRI) and Integrated Crop Management (ICM) have been globally accepted as means of resource conservation. States like Tripura has taken lead in SRI and became a global Leader in SRI. The ICAR Research Complex for NEH Region, Umiam, Meghalaya also initiated work on SRI and ICM since 2004. The results, indicated that ICM recorded the highest productivity, followed by SRI and standard practice. These practices could improve rice productivity by 15-20 % over conventional practice. The SRI and ICM are effective in improving productivity, save resources like seed, time, water etc. and improve soil health. On an average, rice under SRI and ICM establishment methods matures in about 15 and 7 days earlier compared to conventional practice. Therefore, such practices not only conserve resources but also promote crop intensification by early vacating the land earlier for next crop.

Urgent needs to be addressed

- To double agricultural production over the next few decades,
- to reverse the trend of degradation of natural resources, in particular soil, water and biodiversity
- to improve the efficiency of the use of the scarcer production resources
- to address the fact that agriculture and agriculturally induced deforestation cause 30% of the actual green house gas emissions
- to answer the increasing threats of a changing climate to agricultural production

The New Delhi Declaration on CA (4th World Congress on CA, New Delhi)

- To harmonize policies in support for the adoption of CA
- introduce mechanisms which provide incentives for farmers to change their production system to CA.
- pursue the case of CA as the central mechanism for agricultural sector climate change mitigation in the international negotiations for post Kyoto climate change agreement.
- include CA as base concept for the adaptation of agriculture to the challenges of climate change in the National Action Plans for Adaptation.
- support UN FAO in the endeavor to establish a special programme on CA to facilitate this process in its member countries.

The CA approach- new paradigm

Over the past 2-3 decades globally, conservation agriculture has emerged as a way for transition between intensive production systems to sustainable production system. The term conservation agriculture (CA) refers to the system of raising crop without tilling the soil while retaining crop residues on the soil surface. Land preparation through precision land leveling and bed and furrow configuration for planting crops further enables improved resource management.

Conservation agriculture permits management of soils for agricultural production without excessively disturbing the soil, while protecting it from the processes that contribute to degradation e.g., erosion, compaction, aggregate breakdown, loss in organic matter, leaching of nutrient etc. Conservation agriculture is a way to achieve goals of enhanced productivity and profitability while protecting natural resources and environment, an example of a win-win situation. In the conventional system, while soil tillage is a necessary requirement to produce a crop, tillage does not form a part of this strategy in CA. In the conventional system involving intensive tillage, there is gradual decline in soil organic matter through accelerated oxidation and burning of crop residues causing pollution, green house gases emission and loss of valuable plant nutrient. When the crop residues retained on soil surface in combination with no tillage, it initiates processes that lead to improved soil quality and overall resource enhancement.

Basic principles of CA

- Dramatic reductions in tillage (ultimate goal is zero tillage or controlled till seeding for all crops in a cropping system if feasible).
- Rational retention of adequate amount of crop residues on the soil surface. The ultimate goal is surface retention of sufficient crop residues to protect the soil from erosion, improve water infiltration and reduce evaporation to improve water productivity, increase soil organic matter (SOM) and biological activity and enhance long term sustainability.
- Use of sensible crop rotations. Ultimate goal is employing economically viable, diversified crop rotations to help moderate possible weed, disease and pest problems, enhance soil biodiversity, take advantage of biological nitrogen fixation (BNF) and soil enhancing properties of different crops, reduce labor peaks and provide farmers with new risk management opportunities.
- Farmer conviction towards the potential near-term improved economic benefits and livelihoods from sustainable CA systems (ultimate goal is securing farm level economic viability and stability).

Principles of nutrient management in CA

In CA systems, the main principle is 'feed the soil not the plant'. Thus, nutrient management practices in CA systems should pay attention to the following four important aspects:

i. *Biological processes* of the soil are enhanced and maintained for soil organic matter and soil porosity built up.

ii. *Biomass production and biological nitrogen fixation* for keeping soil energy and nutrient stocks sufficient to support higher levels of biological activity and for covering the soil.

iii. *Adequate access to all nutrients* by plant roots in the soil, from natural and synthetic sources, to meet crop needs.

iv. *Soil acidity* is kept within acceptable range for all key soil chemical and biological processes to function effectively.

However, the optimum applications of these techniques will vary across different agro-climatic situations. Specific and compatible management components (nutrient management, weed management, land configuration) will be required to be developed along with their adaptive research with active involvment of farmer's to facilitate adoption of conservation agriculture under contrasting agro-climatic conditions and production systems. The potential benefits of conservation agriculture (Lumpkin and Sayre, 2009) are:

- Increase input use efficiency in crop production.
- Halt and reverse the wide spread degradation of the soil resource base (improve SOC and carbon sequestration).
- Augment crop and soil biodiversity.
- Confront increasing input prices by boosting input use efficiency to reduce production costs.
- Reduce green house gas (GHG) emission from activities related with agriculture.
- Confront the growing shortage of agricultural labor.
- Reduction in fuel and machinery use.

CA - Global and National scenario

Conservation agriculture is practiced in over 95 million hectare (m ha) worldwide (Derpsch, 2005) and currently this area is likely to approach 120 m ha (Lumpkin and Sayre, 2009). It is sobering however, to realize that over 90% of the current area under conservation agriculture based technologies is found in just 5 countries (Argentina, Australia, Brazil, Canada and USA). USA has been the pioneer in adopting CA system and currently more than 18 million ha land is under such system. The spread of CA in US has been the result of a combination of public pressure to fight erosion, a strong tillage and conservation related research and education back up and incentives to adopt reduced tillage systems. Other countries where CA practices have now been widely adopted for many years include Australia, Argentina, Brazil and Canada. Some states of Brazil have adopted an official policy to promote CA.

Conservation agriculture is being adapted to varying degrees in countries of South East Asia viz. Japan, Malaysia, Indonesia, Korea, the Philippines, Taiwan, Sri Lanka and Thailand. Concerted effort of Rice –Wheat Consortium for the Indo –Gangetic Plains (IGP), a CG initiative and the national research system of the countries of the region (Bangladesh, India, Nepal and Pakistan), over the past decades or so are now leading to increase adoption of CA technologies chiefly for sowing wheat crop.

Experience from IGP showed that with zero tillage technology, farmers were able to save on land preparation cost by about Rs. 2500 per ha and reduce diesel consumption by

50-60 liters per ha. Zero tillage allows timely sowing of wheat, enables uniform drilling of seed, improves fertilizers use efficiency, saves water and increases yield up to 20 percent. In India, efforts to adapt and promote resource conservation technology have been underway for nearly a decade but it is only in the past 4 to 5 years that the technologies are finding rapid acceptance by the farmers. Efforts to develop and spread conservation agriculture have been made through the combine efforts of several Agricultural Universities, ICAR Institutes and the CG promoted Rice-Wheat Consortium for the Indo-Gangetic Plains. Unlike, the rest of the world, spread of technologies in India is taking place in the irrigated regions in the Indo-Gangetic plains where rice-what cropping system is dominant. In India efforts to promote CA technologies have largely been focused in the Indo Gangetic Plains covering the states of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal. About 2 million hectare area in IGP are covered under CA practices.

Impact of CA practices

Rapid adoption and spread of CA technologies particularly zero and reduced tillage is attributed to multiplicity of benefits. These include:

- **Reduction in cost of production**: This is a key factor contributing to rapid adoption of zero till technology. Most studies show that the cost of wheat production is reduced by Rs.1500 to 2500 per ha. Cost reduction is attributed to saving on account of diesel, labour and input cost.
- **Reduced incidence of weeds**: Most studies tend to indicate reduced incidence of *Phalaris minor*, a major weed in wheat, when zero tillage is adopted use of weedicide is reduced.
- **Saving in water and nutrients**: Limited experimental results and farmers experience indicate that considerable saving in water (up to 20-30%) and nutrients are achieved with zero till planting and particularly in laser leveled and bed planted crop.
- **Increased yield:** In properly managed zero till planted wheat, yields were higher by 4-6% compared to traditionally prepared fields for comparable planting date.
- **Environmental benefits:** CA involving zero till and surface managed crop residue systems is an excellent opportunity to eliminate burning of crop residues which contribute to large amount of green house gases like CO_2, CO, NO_2, SO_2 and large amount of particulate matter. Burning of crop residues also contributes to considerable loss of plant nutrients, which could be recycled when properly managed. Large scale burning of crop residues is also a serious health hazard.
- **Crop diversification opportunities**: Adopting CA system (including planting on raised beds) offers opportunities for crop diversification. Cropping sequence/ rotations and agro forestry systems when adopted in appropriate spatial and temporal patterns can further enhance natural ecological processes which contribute to system resilient and reduced vulnerability to yield reducing disease/pest problems. Limited

studies indicate that crops like mustard, chick pea, pigeonpea, sugarcane etc. could be adapted to the new systems with advantage.

- **Resource improvement**: No tillage when combined with management of above ground crop residues set in the processes whereby slow decomposition of residues result in soil structural improvement and increased recycling and availability of plant nutrient. Surface residues acting as mulches, moderate soil temperature, reduce evaporation, improve biological activity and provide more favorable environment for root growth, the benefits which are traditionally sought from tillage operations.

Components of CA

The major components of CA includes minimal soil disturbance, maintaining soil cover and crop diversification. The evaluation of various "Conservation Agriculture" technologies for their farm level impact in the country as described below have shown good potential for enhancing input use efficiency at farm level and sustainable farming.

- Land leveling
- Zero-till systems
- Furrow Irrigated Raised Bed (FIRB) planting systems
- Crop residue management
- Crop diversification
- Leaf colour chart

Land leveling: Land leveling is a prerequisite for enhancing the benefits of other resource conservation technologies. In a well leveled field, less amount of water and nutrients are required than an uneven field. The benefits of applying same amount of input will be much higher in a leveled field due to their even distribution. In plains of North India, laser land leveler is used which levels land to an accuracy of ± 2 cm from the average elevation. Only by leveling the land, the yield can be increased by 10-25%, saves water to the tune of 40%, increases nutrient use efficiency by 15-25 % and increases land area by 2 to 6 % due to reduction in area required for bunds and channels (Jat *et al.,* 2004).

The soil moisture status throughout the field governed by its levelness has great influence not only on farming operations but also the yield and input use efficiency. Leveling of land for achieving higher resource use efficiency is not a new technique but the way in which it was done was not up to the mark as frequent patches of dikes and ditches and minimum workable distance are created even with best conventional leveling practices. Undulated land hampers the seedbed preparation, seed placement, germination and also requires heavy draught for machines, which leads to consumption of more energy and ultimately to more cost of production and low productivity levels (Jat *et al.,* 2005).

Zero tillage/reduced tillage system: One of the most important principles of Conservation Agriculture (CA) is minimal soil disturbance. In no-till or zero till system, the seed is placed into the soil by a seed drill without prior land preparation. This technology has been tested and is presently being practiced over 2.0 million hectares in India (RWC-CIMMYT, 2005). This technology is more relevant in the higher yielding, more mechanized areas of north western India, where land preparation is now done with four-wheel tractors. However, in order to extend the technology in Eastern parts of the Indo Gangetic Plains (IGP), drills for small tractors, 2-wheel hand tractors and bullocks have been modified and the drills are made available to the farmers. In India, the burning of non-conventional fuel and resultant emission of greenhouse gases is severe in agriculturally most important region i.e., Indo-Gangetic basin. Rice-wheat is the dominant system of this region wherein conventional method of land preparation/sowing not only disturbs the soil environment but also leads to atmospheric pollution. It is estimated that for each liter of diesel fuel consumed 2.6 kg of CO_2 is released to the atmosphere. Assuming that 150 litres of fuel is used per hectare per annum for tractor uses and irrigation purposes in conventional system, nearly 400 kg CO_2 is emitted per annum per hectare. Hence, in the direction of CA, no-till system has been proved to be an important step in the conservation agriculture and economic growth. Lot of work have been done (Gupta *et al.,* 2005, Ladha *et al.* 2003) which demonstrate the savings on fuel, labour, irrigation water, production cost, energy etc. along with positive effects on soil health and environmental quality in India. Realizing the importance of reduced tillage, farmers across IGP are adapting these systems as it is reducing their cost of cultivation and in turn improving return. Field experiments conducted at ICAR Research Complex for NEH Region, Umiam, Meghalaya during 2009-11 in lowland revealed that minimum tillage enhanced the rice productivity by about 15 % over conventional tillage (Das *et al.,* 2011).

Bed planting systems: Furrow Irrigated Raised Bed (FIRB) or bed planting is a system in which crops are grown on ridges or beds. The height of the beds is maintained at about 15 to 20 cm and a width of about 40 to 70 cm depending on the cops. In case of wheat, around 45 cm bed width is maintained and generally three rows having a distance of 15 cm are sown. The furrow width is generally 25 cm. During the last decade, the practice of raised bed planting has been gaining popularity in IGP. The major concern of this system is to enhance the productivity and save the irrigation water. There are evidences for the greater adoption of this practice in the last decade in other parts of the world like high-yielding, irrigated, wheat growing area of north-western Mexico where bed planting increased from 6 % (farmers) in 1981 to 75% in 1994. The use of raised beds for the production of irrigated non-rice crops was pioneered in the heavy clay soils of the rice growing region in Australia in the late1970s (Maynard, 1991), and for irrigated wheat in the rice-wheat (R-W) areas of the IGP during the 1990s, inspired by the success of beds for wheat-maize systems in Mexico. Potential agronomic advantages of beds include improved soil structure due to reduced compaction through controlled trafficking, and reduced water logging and timely machinery operations due to better surface drainage. In R-W systems in Asia and Australia, permanent beds provide the opportunity for diversification to water logging sensitive crops not suited to conventional flat layouts.

Various trials across IGP revealed irrigation water savings of 12 to 60% for direct seeded (DSRB) and transplanted raised bed (TRB) rice on beds for TRB compared with puddle flooded transplanted rice (PTR) (Balasubramanian *et al.,* 2003). However, many studies at north-west IGP showed little effect of rice on improving water productivity (about 0.30 to 0.35 g kg^{-1}) as decline in water input was accompanied by a similar decline in yield (Sharma *et al.,* 2002).

Crop residue management: Drastic reduction in soil organic matter (SOM) due to residue burning is the key contributor to the un-sustainability of agriculture. Burning crop residues due to lack of efficient technologies for *in-situ* recycling not only leads to loss of considerable amount of NPK and other nutrients but also contributes to global NO_2 budget (Grace *et al.,* 2002). Substantial quantum of crop residues (80.12 million tonne/annum) is available for recycling from rice–wheat cropping systems having nutrient potential of 1.61 (Pal *et al.,* 2002). Design, development and evaluation of new generation drills (happy seeders, rotary disc drill, double disc drill, punch planter etc) are important for the promotion of CA in India.

***In-situ* residue management:** Effective management of residues, roots, stubbles, and weed biomass can have beneficial effect on soil fertility through addition of organic matter and plant nutrients, and soil condition (Singh, 2003). Rice straw contains organic materials and nutrients such as N (0.5–1.5%), P (0.2–1.0%) and K (0.8– 1.0%) (Mongkol and Anan, 2006). It is well documented that the incorporation of organic manure or crop straw into soil improves soil fertility and increases crop yield (Eneji *et al.,* 2001; Singh *et al.,* 2001). The residual effect of incorporating rice straw into the soil provides a significant increase in grain yield after three years of practicing this method (Prasert and Vitaya, 1993). Chutiwat and Direk (1997) reported that incorporating rice straw into soil increased grain yield by 15–18% over burning. It was reported that the application of cattle manure to low fertile soil at a rate of 10 t/ha increased grain yields by 108–106% over no-fertilizer application (Kanika, 1998).

In a study at Umiam, Meghalaya (Subtropical condition) rice-vegetables were grown with minimum tillage. All the weed biomass and crop residues were recycled into the field. Highest grain yield was recorded in cv. Shahsarang 1 (3.70 t ha^{-1}) followed by cv. Vivek Dhan 82 (3.2 t ha^{-1}) and Mendri (3.1t ha^{-1}) and found significantly superior to cv. Manipuri (2.66 t ha^{-1}) (Munda *et al.,* 2006). The nutrients recycled through rice straw ranged from 35.1 kg N/ha with rice -carrot sequence to 42.5 kg N/ha with rice-frenchbean, 9.6 kg P ha^{-1} with rice-carrot to 12.5 kg P ha^{-1} with sole crop of rice and 78.6 kg K ha^{-1} with rice-carrot to 91.9 kg K ha^{-1} in-case of a sole crop of rice. The nutrient recycled through vegetables residue varied from 3.3 kg N/ha with rice-carrot to 87.9 kg N ha^{-1} with rice-potato. In other hand, the nutrient recycled through incorporation of weed biomass ranged from 53.6 to 75.9 kg N, 7.1 to 9.6 kg P and 45.7 to 61.7 kg K ha^{-1}. Microbial population (cfu/g dry soil) in *in-situ* fertility management experiments (Bacteria, 129 x 10^4/g, *Rhizobium*, 61.6 x 10^4/g and

PSM, 39.9 x 10^4 g^{-1}) were much higher than that found under inorganic fertility management (Das *et al.,* 2008).

Green leaf manuring in rice: The fresh N-fixing tree leaves @ 10 t/ha was manually incorporated into the soil as green leaf manure 20 days before transplanting of rice. The nutrient and moisture content of different tree leaves are presented in Table 1. In the first year, highest grain yield (4.82 t/ha) was recorded with recommended NPK (80:60:40 kg/ha) followed by incorporation of *Erythrina* (4.48 t/ha) and *Parkia* leaves (4.13 t/ha). In the following year though the trend remained almost same, but the gap between yield obtained with NPK (5.08 t/ha) and tree leaves incorporation reduced. Surprisingly, in the third year, all the tree leaves except alder surpassed the grain yield level that was obtained with recommended NPK (5.13 t/ha). Significantly highest grain yield of rice in third year was recorded with incorporation of *Erythrina* leaves (5.67 t/ha) that remained at par with *Acacia, Parkia* and *Casia* leaves (Table 1). The result indicated that green leaf manuring with N-fixing tree leaves improved productivity level due to cumulative effect (Das *et al.,* 2009).

Table 1 Effect of different N-fixing tree leaves on productivity of lowland rice

Treatments	Nutrient composition (%)				Grain yield (q/ha)		
	N	P	K	Moisture	2003	2004	2005
Erythrina	3.24	0.47	1.54	73.62	4.48	4.83	5.67
Alder	2.24	0.41	1.37	66.22	3.50	4.10	4.67
Parkia	2.54	0.40	1.52	69.28	4.13	4.40	5.23
Acacia	3.19	0.43	1.36	65.37	3.92	4.66	5.30
Cassia	2.50	0.39	1.17	65.80	3.99	4.55	5.58
Recommended NPK	-	-	-	-	4.82	5.08	5.13
Control	-	-	-	-	2.80	3.13	3.35
CD (P = 0.05)	-	-	-	-	0.60	0.46	0.53

Direct dry seeded and unpuddled transplanted rice

Direct seeding has advantages of faster and easier planting, reduced labour and less drudgery with earlier crop maturity by 7-10 days, more efficient water use and high tolerance of water deficit, less methane and often higher profit in areas with an assured water supply. Thus, the area under direct seeded rice has been increasing as farmers in Asia see higher productivity and profitability to offset increasing costs and scarcity of farm labour (Balasubramanian and Hill, 2002). Weed control is a major issue in direct seeded rice and to overcome this problem, intensive efforts are being made by the agricultural scientist. In some soils, spray of micronutrient like zinc and iron may be needed to remove their deficiency.

Direct seeding of rice using zero till drill, rotary till drill, drum seeder and broadcasting under various field preparation or puddling options was tried at Directorate of Wheat Research, Karnal research farm. Seeding depth was kept at 2-3 cm while using drill for seeding. For comparison purposes transplanting was also done under conventional puddling as well as under zero tillage and after field preparation with rotary tiller (Sharma *et al.,* 2003). The rice variety used was IR 64. Direct seedling was done in the first week of June on the same day when nursery was sown for transplanting. For weed control, Sofit @ 1500 ml/ha was applied after four days of direct seeding followed by one weeding at around 35 days after seeding. Among the direct seeding options, the yield recorded was highest where rice was seeded using rotary till drill followed by broadcasting sprouted rice seed after field preparation by rotary tillage and lowest when broadcasted under zero tillage. The mean yield in rotary tillage was significantly higher compared to zero tillage. Direct drilling by zero till drill and rotary till drill was at par and as good as transplanting under zero tillage. The yield was marginally higher in conventionally puddle conditions compared to transplanting without tillage. Direct seeding of rice under lowland unpuddled condition at Umiam gave promising results (Fig 1) and recorded at par and/or higher yield over conventional puddle transplanted crop. Varieties like Sahsarang 1, Krishna Hamsha performed well. This technology can overcome the problem of water supply for rice transplanting during pre-*kahrif* season and thereby save resources.

Direct wet seeded rice: In this system, sprouted seeds are broadcasted or placed with drum seeder under puddled or unpuddled conditions. Wet direct seeded rice also reduces labour costs. Effective herbicides for weed control have helped making this technology more popular. Seed rate in drum seeded rice varies from 50-75 kg ha^{-1} whereas, in broadcasting method of seeding 40-50 kg/ha is sufficient. In wet seeded rice, puddling can be avoided without any adverse effect on rice yield. The observations at farmers' field showed that mortality of sprouted seed is higher under puddled compared to unpuddled conditions. A field trial on direct seeded rice was conducted with different seed rates varying from 30 to 80 kg ha^{-1} during 2002. Similar yield was recorded at varying seed rates suggesting that the seed rate can be further reduced. In 2003 an additional treatment of seed rate (20 kg ha^{-1}) was included. The varying seed rates were kept based on earlier recommendation of the

Fig 1 Direct dry seeded pre-*kharif* rice (Shahsarang-1)

Directorate of Rice Research (75-100 kg ha^{-1}). The variety used was IR 64 having a 1000 grain weight of about 26 grams. For a population of about $0.33x10^6$ plants/ha recommended for transplanting rice, the seed requirement is likely to be around 11 kg/ha after giving an allowance of 20 % loss in germination of seed. Of rodent and bird damage are further added to the estimates, almost double the seed requirement (20 kg hav) should be good enough. Sowing was done in the first week of July during 2002 and second week during 2003 when the transplanting is generally done. The yield recorded was almost similar at seed rate of 20 to 80 kg ha^{-1} (Sharma *et al.,* 2003).

Crop diversification: Crop diversification is important in mitigating the environmental problems arising on account of monoculture. Inclusion of crops like legume or crop of different habits in rotation and intercropping systems have been found to improve soil heath, reduce weed and pest problems. Choice of appropriate cropping systems and management practices helped minimizing nitrate leaching besides improving N-use efficiency. Inclusion of legumes in cropping systems has been effective in reducing the nitrate leaching in lower profiles. Legume intercropping in cereals grown with wider row spacing has been reported to reduce citrate leaching. Under mid altitude of Meghalaya, rice + soybean and rice + groundnut (4:2 row ratio) has been found economical. Under lowland condition, after harvest of *kharif* rice, pulses like pea and lentil and oilseeds like *toria* were effective under zero tillage condition. Land configuration like raised and sunken bed also promotes crop diversification. In such land configuration, rice is cultivated on sunken beds and vegetables on raised beds.

Leaf colour chart: Leaf colour is a fairly good indicator of the nitrogen status of plants. Nitrogen use can be optimized by matching its supply to the crop demand as observed through change in the leaf chlorophyll content and leaf colour. The leaf colour chart (LCC) developed by International Rice Research Institute (IRRI), Phillipines can help the farmers because the leaf colour intensity relates to leaf nitrogen status in rice plant. The monitoring of leaf colour using LCC helps in the determination of right time of nitrogen application. Use of LCC is simple, easy and cheap under all situations. The studies indicate that nitrogen can be saved from 10 to 15 % using the LCC (Sharma *et al.,* 2008).

CA – some case studies from ICAR Research Complex, Umiam, Meghalaya

i. CA approach in upland rice based cropping system

Two cropping systems (upland rice-*toria* and upland rice-pea) were evaluated under conservation and conventional tillage practices with the objective to conserve soil and moisture. In conservation tillage, residue of all the crops grown in the system along with weed biomass was incorporated. In conventional tillage, crop residues and weeds were removed. It is noticeable that conservation tillage had higher (18%) soil moisture than conventional tillage irrespective of cropping systems which have direct bearing on soil moisture recharge and its uptake by crop.

The growth and yield of all crops (*kharif* and *rabi* season) under conservation tillage was higher than that under conventional tillage. The productivity of *toria* (TS 36) in rice fallow was significantly higher (35%) under conservation tillage compared to conventional tillage. This might be ascribed to the effect of incorporation of plant biomass under conservation tillage which enhanced water retention capacity of soil during crop growing season. Quick build-up of organic matter in conservation tilled plots was possible through incorporation of crop residues and weed biomass in high rainfall area. Based on soil moisture profile, it is revealed that upland rice grown during rainy season under conservation tillage could support second crop of *toria* and pea without any protective irrigation.

The results of another field experiment revealed that rice yield was similar under conventional tillage (2.72 t ha^{-1}) and minimum tillage (2.67 t ha^{-1}). In-situ green manuring with *Crotolaria tetragona* could produce about 5 t/ha of green biomass which was recycled in to the system. However, there was significant effect of residue (nutrient) management practices on rice yield (Table 2). Application of 100 % RDF produced significantly higher grain yield (3.48 t/ha) of rice compared to all other treatments. Among the residue management practices, application of 50 % RDF + rice straw 5t ha^{-1} (applied 2 months before sowing and incorporated) recorded maximum grain yield (2.71 t ha^{-1}) followed 50 % RDF + fresh biomass *Eupatorium* 10 t ha^{-1} (2.61 t/ha). The productivity of succeeding *toria* was better under plots where minimum tillage was done for *kharif* rice followed by zero tillage (563 kg ha^{-1}) compared to conventional tillage for *kharif* crop and zero tillage in *toria* (506 kg/ha). Among the subplot treatments, *toria* yield was maximum where 100 % RDF was applied to preceding rice (652 kg ha^{-1}) followed by application of 50 % RDF + Rice straw 5 t/ha (624 kg ha^{-1}) to *kharif* rice (Fig 2).

Table 2 Productivity of rice-*toria* system as influenced by tillage and residue management practices

Treatments	Rice (t ha^{-1})	*Toria* (kg ha^{-1})
Tillage		
Conventional tillage	2.72	506
Minimum tillage	2.67	563
Residue management practices		
100% recommended dose of fertilizer (RDF 60:60:40 kg/ha)	3.48	652
50 % RDF	2.47	514
50 % RDF + rice straw 5 t/ha	2.71	624
50 % RDF + green manuring (1:1)	2.66	613
50 % RDF + fresh biomass of *Eupatorium* 10 t/ha	2.61	423
Farmers practice (FYM 5 t/ha)	1.98	398

Fig 2 Zero tillage *Toria* (TS 36) in terrace after rice

ii. CA approach for rice based system in valley upland

In flat or valley upland, rice is the common crop. Because of water stress, second crop is not grown in rice fallows. In a field study, pea was sown without any tillage (zero tillage) by dibbling after harvest of rice. At the time of rice harvest, three residue levels (*1/3* residue, ½ residue and complete removal of residue) were maintained with the hypothesis that residue kept in the field could maintain soil moisture required for pea. Zero-tilled peas were sown by hand dibbler in all the plots. In rice fallow, better pea performance was found under 75% rice residue retention plots, followed by 50% rice residue retention (Fig 3). In case of complete removal of rice residue, seeds of pea germinated but failed to grow thereafter due to insufficient soil moisture to support crop growth. Zero tillage system without crop residue left on the soil surface have no particular advantage because

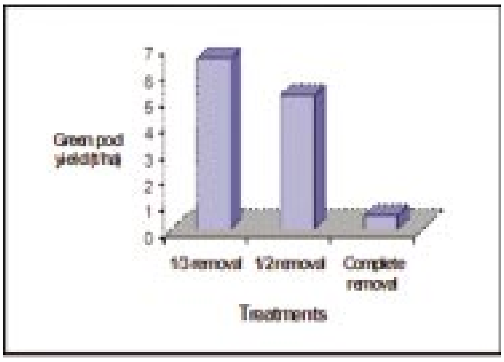

Fig 3 Green pod of pea under varying degree of residue removal

of the water loss from the surface, as was evident from soil moisture and yield data (Ghosh *et al*., 2010).

iii. CA approach for lowland rice based system

Harvesting of rice at ground level is a common practice in North East region and rice straw is mostly used for fodder. Those farmers who do not keep any livestock, usually burn residue after its harvest. Similarly, in traditional rice cultivation, farmers plough the field several times before sowing, particularly during puddling which leads to destruction of soil structure and loss of organic carbon from the soil. As soil carbon is designated as *black gold* of soil, an optimum level of soil organic carbon (SOC) is needed to conserve soil, water and nutrient; favour biological activity and high productivity in any system. Many a times, sowing of *rabi* crops is not possible after harvest of puddled rice because of poor soil structure and soil fertility. Tillage affects soil physical, chemical and biological properties and can play an important role in enhancing the yield potential of crops. Resource conserving practices like zero tillage can help farmers to grow crops sooner after rice harvest so that the grain matures before the onset of pre-monsoon shower besides conserving moisture, nutrient and soil-C.

A field study was conducted for four years in rice (*kharif* season) with four tillage practices *viz*., T_1 conventional tillage, (3-4 passes of power tiller and residue removal), T_2 double no-till and residue retention (1/3), T_3 no-tillage for *rabi* crops and residue retention (1/3), T_4 residue incorporation (minimum tillage) (one power tillage before sowing) and 3 *rabi* crops (wheat, linseed and mustard). Except no till double plots, puddling was done in other treatments. In double no-till, transplanting of 25 days old seedlings (3-4 seedlings/hill) with the help of cone of manual dibbler at spacing of 25 x 10 cm row-to-row and plant-to-plant was done in moist field. Ponding of water was avoided at the time of transplanting. Glyphosate (Roundup) @ 3 ml l^{-1} was applied two weeks before the transplanting. After transplanting, 5-6 cm water was maintained through proper bunding. The results revealed that maximum grain yield of rice (rainy season) and following crops (wheat, *toria* and linseed) were recorded under double no till followed by no till (for *rabi* crop only) along with residue retention (Table 3).

Table 3 Seed/grain yield (kg ha^{-1}) under different tillage practices (average of 4 years)

Crop	Conventional tillage (Residue removal)	Zero tillage (Residue etention and double no-till)	Zero tillage (Residue retention and no-till for *rabi* crop)	Minimum tillage (Residue incorporation)	CD (P=0.05)
Rice	3166	4564	4371	4176	632
Wheat	2257	3452	3317	2761	493
Toria	512	832	775	625	220
Linseed	300	479	421	375	134

Significant difference in SOC was found among tillage treatments. In the field study, no-till also recorded higher soil microbial biomass carbon (SMBC), dehydrogenase activity and earthworm population (Table 4), which in turn resulted in growth and higher yield of all crops under zero tillage. When zero tillage was combined with residue on soil surface, C – sequestration was higher than conventional tillage which favoured more number of earthworm population in the field (Ghosh *et al*., 2010).

Table 4 Organic carbon and biological activity under different tillage practices (four years pooled data)

Treatment	SOC (%)	SMBC (µg/g soil)	Dehydrogenase activity (µgTPF/g/24h)
Conventional tillage	1.47	91.3	29.5
Zero tillage	2.23	128.5	131.5
double no-till	2.51	134.1	166.6
Minimum tillage	2.17	121.3	127.5
CD (*P*=0.05)	0.78	12.1	27.5

In another study, the effect of tillage and plant biomass management practices on productivity of lowland rice (var. Shahsarang-1) was studied. The main plot treatments included tillage practices *viz.* conventional (4 ploughings) and minimum tillage (2 ploughings), while the sub-plot treatments were plant biomass management *viz.* 50 % NPK, 50% NPK + fresh weed biomass 10t/ha (*Ambrosia* + *Eupatorium*), 100 % NPK (80: 60: 40 kg/ha), 50% NPK + green leaf manure (fresh *Tephrosia* biomass 10t/ha) and 50% NPK + *in-situ* residue management (rice straw 5 t/ha approx.) and FYM 10t/ha + weed biomass 10t/ha + Rock Phosphate 150 kg/ha (100 % organic). Among the two tillage practices, minimum tillage gave the higher yield of rice in terms of grain, straw and total plant biomass yield. On an average, minimum tillage recorded 15 % higher grain yield over conventional tillage. Among the nutrient management practices, 100% NPK (5.45 t/ha) was the most efficient in increasing grain yield of rice followed by 50% NPK + fresh weed biomass 10t/ha (*Ambrosia* + *Eupatorium*) (5.37t/ha) both of which were significantly superior to 50 % NPK alone and 100 % NPK through organic sources (Table 5).

iv. CA in rice for enhancing resource use efficiency and crop diversification

The conventional-zero tillage showed superior results compared to the other treatments and was followed by conventional-conventional and conventional - Furrow and raised beds (FRB). This resulted in a similar trend in the yield of the crop (Table 6) where conventional-zero tillage was the highest yielder followed by conventional-conventional and conventional-FRB (Fig 4).

Table 5 Productivity (t/ha) of rice as influenced by tillage and residue management practices in lowland

Treatments	Grain	Straw
Tillage		
Conventional tillage	4.78	6.40
Minimum tillage	5.53	6.66
CD (P =0.05)	0.09	0.12
Residue management practices		
50 % RDF	4.52	6.47
50 % RDF + fresh biomass of *Eupatorium* 10 t/ha	5.37	6.57
100% RDF (80:60:40 kg/ha)	5.47	6.89
100 % organic (Rice straw 5 t/ha + *Eupatorium* 10 t/ha + Rock phosphate 150 kg/ha)	4.94	5.98
50 % RDF + green leaf manuring (1:1)	5.35	6.58
CD (P =0.05)	0.15	0.21

Fig 4 Pea and lentil on FRB

Table 6 Yield attributes and yield of rice under various tillage systems

Treatment	Panicle/m^2	Effective grains /panicle	1000 grain wt. (g)	Grain yield (kg/ha)
Conventional - Conventional	322	94.4	23.7	4250
FRB – FRB	350	69.6	24.9	3850
Conventional - FRB	272	108.8	23.2	4125
Conventional – Zero Tillage	248	107.6	24.1	4750

After rice harvest, pulses like pea and lentil and mustard (TS 36) were sown as per the treatment. The productivity of all the *rabi* crops were highest under FRB (Fig 4) followed by zero tillage. The soil moisture status was also higher under FRB followed by zero tillage plots compared to conventional tillage plots. Therefore, RCTs like FRB and zero tillage improved productivity, conserved soil moisture, promotes crop diversification and reduced cost of cultivation.

v. Zero tillage – a viable option for pulse production in rice fallow

Conventionally after *kharif* rice, fields remain fallow in lowland, mainly due to excess moisture owing to seepage from surrounding hillocks in mid altitude. Draining water from rice field at physiological maturity creates favourable condition for cultivation of *rab*i pulses like pea, lentil etc. A simple drainage around the rice fields/plots with appropriate outlets creates the desirable situations.

To study the performance of pulses like pea and lentil, 4 varieties each of pea and lentil were obtained from IIPR, Kanpur, UP during 2009. Pea and lentils (Fig 5) were grown under zero tillage in lowland rice fallow using recommended dose of NPK (20:60:40 kg/ha). One weeding cum hoeing was given manually at 30 DAS. In another trial, different lentil varieties were also grown as utera crop. The lentil seeds were broadcasted a day before rice harvest and the seeds were partially incorporated into the soil during harvesting. A seed yield of about 500 kg/ha was been obtained from *utera* lentil.

The average productivity of green pea were 6.20, 6.75 and 5.25 t/ha, respectively under ZT, MT and CT and the average productivity of lentil seeds were 1.17, 1.42 and 0.96 t/ha, respectively. Retention of 40 cm standing stubble resulted 48 % enhancement in lentil productivity under zero tillage in lowland rice fallow. The soil organic carbon enhanced by 12.5 % due to double no tillage over conventional tillage after 3 cropping cycles in rice-pea cropping system.

Therefore, pea and lentil increased the system productivity and farm income. With appropriate agronomic interventions and varietal screening, pea and lentil could be popularized in mid altitude for food and nutritional security of small and marginal farmers especially the tribal farmers of the region**.**

Fig 5 (a) Rice under resource conservation practice (b) Opening furrow by manual furrow opener, placing fertilizer, seeds and covering of seeds (c) Good lentil crop in between rice stubbles (d) Good pea and lentil crop under zero tillage

Conservation agriculture and GHG emission

The CA (reduced tillage, residue management and crop diversification) offers the most practical solution for the food and nutritional security in hill region of North East India. The atmospheric CO_2 increased from 280 ppm during 1750 to 370 ppm by 2000. The atmospheric CO_2 is currently increasing at the rate of 0.5% per annum. The impact of enhance CO_2 concentration on agriculture need to be thoroughly understood and appropriate management practices has to be worked out. It is estimated that for each litre of diesel burnt about 2.6 kg CO_2 is released in atmosphere. The soil (2500 Pg) is considered as the greatest C-sink after ocean (38000 Pg) and forest. The C-sequestration potential of CA is estimated to be 1.8 t CO_2/ha/year. By sequestering of 1 tonne carbon in humus, we can conserve 83.3 kg N, 20 kg P and 14.3 kg S/ha. Manipulating cultivation practices, balance fertilization, alternate wetting and drying reduces CH_4 emission substantially. Use of slow release N fertilizer, nitrification inhibitor etc. may reduce N_2O emission. Manipulating animal husbandry practices particularly feeding management and adoption of efficient species will reduce CH_4 emission significantly.

Constraints in adopting conservation agriculture system

Conservation agriculture poses a challenge both for the scientific community and the farmers to overcome the past mindset and explore the opportunities that CA offers for natural resources improvement. CA is now considered a route to sustainable agriculture. Spread of CA therefore will greatly call for strengthening research and linked development efforts. Some of the major constraints are-

1. Although significant successful efforts have been made in developing and promoting machinery for seeding crops in zero till system, successful adoption of CA system will call for greatly accelerated effort in developing, standardizing and promoting quality machinery a range of crop, cropping sequences, permanent bed and furrow planting system, harvesting operations to manage crop residues etc.
2. Conservation agriculture system represents major departure from the past way of doing things. This implies that the whole range of practices including planting and harvesting, water and nutrient management, disease and pest control etc. need to be evolved, evaluated and matched in the context of new system.
3. Managing CA systems will be highly demanding in terms of knowledge base. This will call for greatly enhanced capacity of scientist to address problems from a system perspective; be able to work in close partnership with farmers and other stakeholders and strengthened knowledge and information sharing mechanism.
4. In the context of North East India, mechanization is an important constraint in popularization of CA. However, there is ample scope for light and small machineries/ implements in serving the cause of CA.

Conclusions

The agricultural technologies need a shift from production oriented to profit oriented sustainable farming in the changing agricultural and climatic scenario. In this direction, the pace of adoption of resource conserving technologies (RCTs) by the Indian farmers is an earnest attempt. The CA system will promote equity and livelihood of farmers and save natural resources for posterity. Appropriate policy decision coupled with technological back up would certainly help in adoption of at least some of the CA approaches, thereby sustaining the agriculture in the NE region.

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Improved Management Practices for Carbon Management and Mitigation of Climate Change

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Introduction

Climate change is one of the most important global environmental challenges facing humanity with implications for food production, natural ecosystem, fresh water supply and health care (Sathaye *et al.*, 2006). Increase in atmospheric carbon dioxide (CO_2) and other greenhouse gases *viz*., methane (CH_4), nitrous oxide (N_2O) and CFC due to fossil fuel burning, rapid industrialization, deforestation and increased agricultural activities reduce the escape of earth's radiation to space. This results in consequent warming earth's surface as well as lower atmospheric layer. Observational evidences show that many natural systems are being affected due to global warming.

Agriculture is the largest employer in the world. Simultaneously agriculture is also the most vulnerable to weather and climate risks. At present 40% of earth's land surface is managed for cropland and pasture. In the developing countries, about 70% of total population is dependent on agriculture. The losses in crops in the world agriculture are mainly due to direct impacts of aberrant weather *viz*., drought, floods, untimely rain, frost, hail, heat and cold waves and severe storms (Hay, 2007). The impact of projected changes in climate (*viz*., change in temperature, precipitation and concentration of CO_2 rise in atmosphere) would induce changes in many aspects of biodiversity. The winter season will be affected the most (Table 1) due to climate change as compared to the other seasons.

Table 1 Climate change impacts in different crop seasons in India

Year	Season	Increase in temperature (°C)		Change in rainfall (%)	
		Lowest	Highest	Lowest	Highest
2020s	Winter	1.08	1.54	-1.95	4.36
	Kharif	0.87	1.12	1.81	5.10
2050s	Winter	2.54	3.18	-9.22	3.82
	Kharif	1.81	2.37	7.18	10.52
2080s	Winter	4.14	6.31	-24.83	-4.50
	Kharif	2.91	4.62	10.10	15.18

(Source: Kashyapi *et al*., 2009)

The climate change has the potential to change significantly the productivity of agriculture. Some high productive areas may become less productive and *vice versa*. The production of rice, maize and wheat in the past few decades has declined in many parts of Asia due to increasing water stress arising partly from increasing temperature and reduction in number of rainy days (Tao *et al*., 2004).

In India, one of the major sources of greenhouse gases (GHGs) is biomass burning (Fig 1). In Indo-Gangetic plains, space based observations showed that out of total fire events around 69% contribution comes from agricultural areas. This is mainly due to intensive cultivation in this belt. It has also been reported that 84% agricultural residue burning is from rice-wheat system and remaining 16% from other types of crop rotations. The fire incidents are reported very high in October-December (55%) compared to that in March-May (36%) indicating that burning of rice residue is more prevalent than wheat.

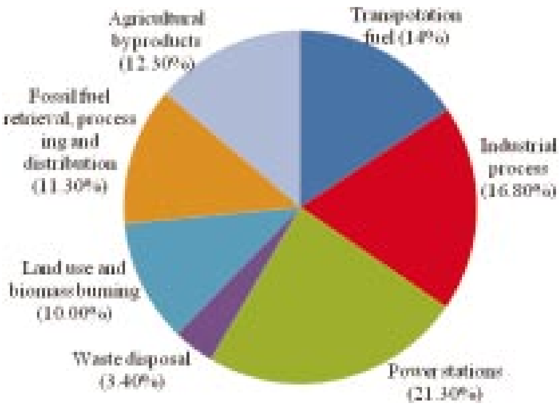

Fig 1 Greenhouse gas emission by different sectors
(Source: http://en.wikipedia.org)

Effect of elevated greenhouse gases on agriculture

- Rising CO_2 concentration have both positive and negative consequences on agriculture.
- CO_2 leads to fewer stomata development on plants which leads to reduced water usage.
- Quality of food grains decreases.
- Faster depletion of soil organic carbon (SOC).
- More extreme rainfall events.
- Drought and floods.
- Because of higher temperatures and humidity, there could be increased pressure from insects and diseases.

Resource conservation technologies for mitigating climate change

Increase soil carbon

Historically, agricultural practices have caused large carbon losses from cropland soils. If half or more of the original carbon stock of croplands could be regained, tens to hundreds of million metric tons of carbon could be stored (i.e., added to and sequestered) in soils annually over the next several decades. Carbon additions to soil are favoured by management practices that increase plant residues. Slower the rate of soil organic matter decay, higher will be the soil carbon stocks. Land-use changes such as conversion of annual cropland to grassland or forest and restoration of degraded lands can also increase soil carbon and reduce GHGs emissions (Table 2). A number of management practices are available to increase cropland soil carbon inputs. Increasing soil carbon inputs by increasing the productivity of crops is largely in line with farmers' management goals of achieving high productivity. Carbon inputs to soil can also be increased by using crop rotations with higher residue yields, by reducing or eliminating the fallow period between successive crops in annual crop rotations, and by making efficient use of fertilizer and manure. On annual croplands, soil carbon losses can be reduced by decreasing the frequency and intensity of soil tillage, in particular through conversion to no-till practices.

Table 2 Options to mitigate GHG emissions from agriculture

Technical options	Climate and other environmental effects
Reduce fossil energy use	• Reduced CO_2 emissions of 10-50 mt C yr^{-1}
• Reduce tillage	
• Reduce fertilizer use	
• Irrigation scheduling	
Increase C storage in agricultural soils	
• Reduce tillage	• Increased C storage of 440-880 mt C yr^{-1}
• Improve residue management	• Reduced soil erosion
• Restore productivity of degraded soils	• Increased food production on balance of options
Improve rice production practices	
• Water management	• Reduced CH_4 emissions of 8-35 mt CH_4 yr^{-1}
• Nutrient management	
• Low methane cultivars	
Increase N fertilizer use efficiency	
• Improved application methods	• Reduced N_2O emissions of 0.4-1.1 mt N_2O yr^{-1}
• Match N supply with crop needs	• Improved water quality
• Maximize manure use	
• Optimize tillage, irrigation and drainage	
Improved management of ruminant livestock	• Reduction in methane production (mt CH_4 yr^{-1})
• Improved diet quality and nutrient balance	10-35
• Increase feed digestibility	1-3
• Improved animal genetics and reproduction	1-6

(Source: Watson *et al*., 1996)

Use of high-residue crops and grasses

Annual crops that produce large amounts of residues (plant matter left in the field after harvesting), such as corn and sorghum, typically result in higher soil carbon levels than many other crops. Hay and pasture lands also tend to have high carbon inputs because perennial grasses allocate a large portion of their total carbon assimilation to root growth. For example, long-term experiments at two sites in Ohio (Dick *et al*., 1998) shown that about ten tonnes per hectare more soil carbon was found after 30 years under continuous corn crops or with corn-oat-hay rotations than for corn-soybean rotations. This is equal to an average gain of 0.3 tonnes per hectare per year. Conversion from continuous cereal cropping to cereal-hay rotations was estimated to increase soil carbon by about 1 percent per year, or about 0.5 t ha^{-1} yr^{-1}, for average European conditions (Smith *et al*., 1997).

Reduction or elimination of fallow periods between crops

In semi-arid regions like the Great Plains, summer fallow (a practice where soil is left unplanted for an entire cropping year) was developed as a way of storing soil moisture to improve yields and reduce crop failure. However, summer fallow practices caused high rates of soil carbon loss and soil degradation in large areas of the western United States (Haas *et al*., 1957). More recently, new cropping systems that combine winter wheat with summer season crops (e.g., corn, sorghum, millet, bean, sunflower) in rotation using no-till practices (see below) have proved successful in both improving soil moisture and increasing soil carbon (Peterson *et al*., 1998). In more humid regions, where fields may be left fallow in winter, it is often feasible to grow winter cover crops, usually legumes or annual grasses, and thus maintain vegetation round the year. Cover crops serve several functions, including taking up excess soil nutrients (e.g., nitrogen) to reduce leaching or other losses to the environment, fixing atmospheric nitrogen (e.g., legumes), and controlling weeds; but they also serve to augment the input of plant residues, thereby increasing soil carbon content.

Efficient use of manures, nitrogen fertilizers and irrigation

As a general rule, promoting the efficient use of inputs such as fertilizer, manure, and irrigation will yield the best results for GHG mitigation (Paustian *et al*., 2000). Efficiency in this context is defined as maximizing crop production per unit of input. If high rates of crop production (with attendant carbon input increases) are achieved primarily through increased nitrogen fertilization and irrigation, increases in other GHG emissions, particularly nitrous oxide can offset part or all of the gains in soil carbon. Tailoring fertilizer and manure applications to satisfy crop nitrogen demands, so that less nitrogen is left behind in the soil, can reduce nitrous oxide emissions while building soil carbon stocks. Efficient use of irrigation water will similarly reduce nitrogen losses including nitrous oxide emissions, and minimize CO_2 emissions from energy used for pumping while maintaining high yields and crop-residue production.

Use of low or no-till practices

Reducing soil carbon losses on croplands is primarily accomplished through reducing the frequency and intensity of soil tillage. Soil tillage tends to accelerate organic matter decomposition (including the oxidation of carbon to CO_2) by warming the soil, breaking up

Table 3 Amount of carbon sequestered in a long-term fertilizer experiment

Treatment	Organic C sequestered (kg ha^{-1} yr^{-1})		
	SOC	POC	$KMnO_4$ C
50% NPK	58	10	16
100% NPK	135	21	46
150% NPK	553	37	62
100% NP	120	19	27
100% N	101	14	24
100% NPK + FYM	997	70	76

(Source: Purakayastha *et al*., 2008)

soil aggregates and placing surface residues into the moister environment within the soil (Reicosky, 1997; Six *et al*., 2000). Traditional tillage methods such as mold-board ploughing, which fully inverts the soil, cause the greatest degree of disturbance and consequently tend to cause the most degradation of soil structure and loss of soil carbon stocks. In many areas, the trend over the past several decades has been towards reduced tillage practices that have shallow depths, less soil mixing, and retention of a larger proportion of crop residues on the surface. No-till, a practice in which crops are sown by cutting a narrow slot in the soil for the seed, and herbicides are used in place of tillage for weed control, causes the least amount of soil disturbance. In recent reviews (Ogle *et al.,* 2005) analyzed data from 126 studies worldwide and estimated that soil carbon stocks in surface soil layers (up to 30 centimeter depth) increased by an average of 10 to 20 per cent over a 20-year time period under no-till practices compared with intensive tillage practices. The relative increases in carbon stocks were higher under humid than dry climates and higher under tropical than temperate temperature regimes. Finally, CO_2 emissions from machinery use are decreased by 40 per cent for reduced tillage and 10-70 per cent for no-till, relative to conventional tillage (West and Marland, 2002), contributing to further reductions in GHGs from reducing tillage intensity. Management activities can include boosting plant productivity through fertilization, irrigation, improved grazing, introduction of legumes, and use of improved grass species. Intensive management strategies are usually restricted to more humid regions with high productivity potential or regions where irrigation is used. Average rates of carbon increase were approximately 0.3 t ha^{-1} yr^{-1} for fertilization and improved grazing systems and approximately 0.7 t ha^{-1} yr^{-1} for introduction of legumes.

Soil carbon sequestration potential

Carbon sequestration rates vary by climate, topography, soil type, past management history, and current practices. Various global and national estimates for potential soil carbon sequestration have been made. These estimates are usually based on overall carbon gain for

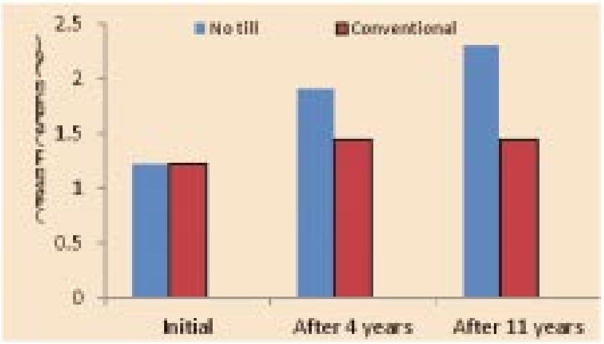

Fig 2 Effect of tillage practices on soil organic carbon
(Source: Bessam and Mrabet, 2003)

a suite of practices and the available area on which these practices could be applied, resulting in estimates of biological or technical potential. Paustian *et al.* (1998) estimated a global potential from improved agricultural soil management of 400 to 600 MMT of carbon per year, and the Intergovernmental Panel on Climate Change estimated potential rates from improved cropland, grazing land, and agroforestry of 390 MMT of carbon per year by the year 2010 and 780 MMT of carbon per year by 2040, assuming a lag-time in the adoption of improved practices. Lal *et al*. (2003) estimated an overall potential for soil carbon sequestration (excluding forest related activities) of 70 to 221 MMT of carbon per year for a combination of practices including land set-asides, restoration of degraded lands, conservation tillage, irrigation and water management, and improved cropping and pasture systems. This overall figure represents net increases, taking into account increased GHG emissions associated with the management improvements. There are numerous uncertainties surrounding such estimates of carbon sequestration potential. Development of new technologies specifically targeted at increasing soil carbon (through plant breeding or new soil amendments) could increase potentials. On the other hand, rising temperatures due to global warming will likely stimulate soil organic matter decomposition, which may reduce or eliminate the potential to further increase soil carbon stocks. Finally, the amount of carbon sequestration which is actually achieved will depend on economic, social, and policy factors and is likely to be substantially less than the biological and technical potential.

Reducing agricultural nitrous oxide and methane emissions

Despite challenges, there is considerable scope for reducing emissions of gases like nitrous oxide (N_2O) and methane (CH_4). Nitrous oxide constitutes the largest agricultural source of GHG emissions in terms of warming potential (48 per cent). A characteristic of modern agriculture is the huge increase in nitrogen supplied—not only as mineral fertilizer but also through nitrogen-fixing leguminous crops and animal manure—to boost crop productivity (Mosier *et al*., 2001). N_2O emissions are strongly influenced by the availability of nitrogen in soil. However, control on the amount, timing, and placement of fertilizer can minimize these emissions. Methane emissions from agricultural soils are mainly associated with flooded soils such as rice-growing areas and wetlands. Most soils are not a major source of CH_4, and in fact, most non-flooded soils remove some amount of CH_4 from the atmosphere.

i. Nitrous oxide

Unlike the case for CO_2 and CH_4, there are no significant biological sinks for atmospheric N_2O. Since agricultural N_2O emissions correlate with the amount of nitrogen available in soils, mitigation rests largely on increasing the efficiency of nitrogen use without compromising crop yields. Using nitrogen more efficiently means better matching its availability to plant needs. However, because of variable weather conditions, it is necessary to predict crop nitrogen needs at the start of the growing season when most fertilizer is applied. Major cropland area (especially rice-wheat system) is rated as having high nitrogen balances, resulting in that contribute substantial amount of N_2O to the atmosphere and nitrate (NO_3) to water bodies. Where animal manure is applied, farmers may not adequately account for its nitrogen contributions and, therefore, add too much supplemental fertilizer. With increasing size and concentration of confined animal feeding operations (CAFOs), manure supply and transport costs lead to application of manure at higher than recommended rates on nearby fields. In addition to application rate, timing is a factor in the efficiency of nitrogen use. Applying fertilizer only after the start of the growing season (ideally as split applications over time) provides better synchrony with plant demands because crop uptake capacity is low at the beginning of the growing season, increases rapidly during vegetative growth, and then drops sharply as the plant nears maturity. Slow-release fertilizers, such as sulfur-coated urea, which delay the release of fertilizer applied at planting time until plant nitrogen uptake capacity is higher, can also be used. Where and how fertilizer is applied also influences the efficiency of nitrogen use. Surface application of fertilizer and manure is subjected to greater volatilization losses, predominantly as ammonia gas, than injected fertilizer. Ammonia is eventually deposited downwind in environments where it may result in N_2O emissions. Fertilizer application into the soil, near the active root uptake zone, reduces nitrogen losses and increases plant nitrogen use, resulting in less residual nitrogen that can be lost as N_2O.

ii. Methane

Methane is produced in soils by bacteria, termed methanogens, which function under strictly anaerobic (oxygen-free) conditions. Consequently, CH_4 emissions from agricultural soils are largely restricted to flooded soils, such as those used for rice cultivation and other cultivated wetland crops (e.g., cranberry bogs), where water-saturated conditions inhibit the diffusion of oxygen into much of the soil. Potential mitigation options include changes in strategies for crop breeding and management of water, fertilizer, and residues. Perhaps most promising is the selection and breeding of new rice varieties that are less conducive to transport of CH_4 through the plant to the atmosphere (Aulakh *et al*., 2002). Because 60 to 90 per cent of CH_4 emission from growing rice occurs via transport through the plant tissues, choosing rice cultivars with a high resistance to CH_4 transport could reduce emissions by as much as 50 per cent (Sass, 1994). Under aerobic (oxygenated) conditions, other soil bacteria consume CH_4, oxidizing it to CO_2. Because CH_4 has a Global Warming Potential (GWP) 21 times greater than CO_2, the conversion of CH_4 to CO_2 yields an overall decrease in total

GHG warming. Globally, soils eliminate about 20 to 60 MMT of CH_4 per year (115 to 345 MMT carbon-equivalent) through oxidation. The highest rate of CH_4 oxidation occurs in undisturbed, native ecosystems. Cultivated soils have much lower rates of CH_4 oxidation—for example, CH_4 oxidation was reduced by 80 per cent in annual cropland compared with deciduous forests (Robertson *et al*., 2000). Similar reductions (80 to 90 per cent) were found when cropland was compared with native prairie (Bronson and Mosier, 1993). In general, conversion of marginal cropland to permanent set-aside and use of no-till methods on annual cropland are the practices that will be most beneficial to strengthening the CH_4 sink on agricultural soils.

Table 4 Effect of nitrogen doses on methane emission from rice fields

Urea doses (kg ha^{-1})	Methane emission (kg ha^{-1})
0	210
100	300
200	310
300	370

(Source: Lindau *et al*., 1991)

Table 5 Effect of nitrification inhibitors on methane production in flooded rice soil

Treatment	Methane production (CH_4 kg^{-1} soil)				
	5 DAF	10 DAF	20 DAF	30 DAF	40 DAF
None	47bc	126a	168a	2929a	4426c
Sodium azide	40c	42c	58d	451g	1795g
Aminopurne	56bc	82b	140b	2066b	3540b
Pyridine	52bc	87b	130bc	1558d	4094d
Dicyanmide	39c	50c	63d	1112f	2844f
Thiourea	95a	103ab	110c	1843c	4791b
Amonium thiosulphate	71b	90d	125bc	1433e	5098a

DAF = Days after flooding (Source: Bharati *et al*., 2000)

iii. Biological N-fixation

The amount of N fixed by biological N fixation in agricultural systems and the nitrous oxide conversion coefficient are uncertain. Biological nitrogen fixation (BNF) supplies globally 90 to 140 Tg N per year to agricultural systems (Peoples *et al*., 1995). Although more verification on these figures is necessary, most indications are that BNF contributes more N for plant growth than the total amount of synthetic N fertilizers applied to crops each year (Danso, 1995). The Phase I IPCC guidelines (IPCC, 1995) mentioned about equal rates. On an average, BNF supplies 50-60% of the N harvested in grain legumes, 55-60% of the N in nitrogen fixing trees and 70-80% of the N accumulated by pasture legumes (Danso, 1995). Cultivation of grain legumes, however, often results in net soil N depletion. Because of the uncertainty in knowing the amount of dinitrogen fixed during N-fixation (Peoples *et al.*, 1995) and the lack of country data on N-fixing crops, it is difficult to assign a conversion factor to nitrous oxide emission that is related to the amount of N fixed by a crop. Total N input is estimated by assuming that total crop biomass is about twice the mass of edible crop, and a certain N content of N fixing crop. This crop production is defined in FAO crop data bases as "pulses and soybeans". The N-fixation contribution does not include nitrous oxide produced in legume pastures. This nitrous oxide production is at least partially accounted for emissions from pastures that are being grazed.

iv. Crop residue

There is only limited information concerning reutilization of N from crop residues applied to agricultural lands. Although the amount of N that recycles into agricultural fields through residues may add 25-100 Tg N yr^{-1} of additional N into agricultural soils (mainly from crop residues) the exact amount converted to nitrous oxide is not known. Nitrous oxide emissions associated with crop residue decomposition are calculated by estimating the amount of N entering soils as crop residue. The amount of nitrogen entering the crop residue pool is calculated from crop production data. Since data only represent the edible portion of the crop, these must be roughly doubled to estimate total crop biomass. Some of the crop residue is removed from the field as crop (approximately 45%), and some may be burned (approximately 25% of the remaining residue in developing countries), or fed to animals. The amount of N in crop residue actually returned to a field is uncertain, as is the amount of time required for the N to mineralize. Neither the amount of root biomass remaining in the soil nor the amount of plant residue fed to animals is accounted for in this crop residue estimate.

Conclusion

The climate *change* is one of the most potent environmental challenges that have great implications on global food production system. The faulty agricultural practices like continuous tillage and traditional method of rice cultivation add considerable amount of greenhouse gases to the atmosphere. Many resource conservation practices have been identified by the researchers which reduce the emission of greenhouse gases from agricultural lands. Therefore, to avoid the risk of climate change, resource conservation practices which mitigate the emission of greenhouse gases needs to be promoted to meet out the food demand of the ever increasing population in future.

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Methods for Calculating Soil Organic Carbon Stocks and Fractions in Soils of North-East Hill Region of India

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Introduction

Soil carbon cycles are closely linked to agricultural productivity and can be influenced by changes in land use, thus having important implications for global climate change. Soil–plant systems can act as sinks or sources of atmospheric CO_2 depending on formation and decomposition rates of soil organic matter (SOM). Soils contain more than twice the amount of organic C found in the terrestrial biota or the atmosphere, and approximately one third of the global soil C pool is in the tropics. Therefore, changes in tropical soil C pools could have significant impacts on the global C cycle. Soil organic C dynamics can be influenced by climate and land-use changes (Purakayastha *et al*., 2007) and soil management practices (Xu *et al*., 2008). There is much concern that land-use change may have significant feedbacks on the global C cycle. Deforestation in the tropics has resulted in loss of soil productivity through reduction in organic C concentration and consequent loss in aggregate stability. Changes in SOM appear to depend on previous land use, the type of vegetation established, and other factors (Paul *et al*., 2002).

Soil organic matter (SOM) is the central element of soil fertility, productivity and quality, as reduction in SOM is believed to create an array of negative effects on crop productivity. It becomes highly essential to maintain and improve its level in the soil and is a pre-requisite to ensuring soil quality, future productivity, and sustainability (Katyal *et al*., 2001). Soil organic matter, the organic fraction of the soil, is a complex mixture of plant and animal products in various stages of decomposition, soil microbes, and substances produced by them. The importance of organic carbon to the physical, chemical, and biological aspects of soil quality is well recognized. The SOM is an extremely important attribute of soil quality and soil health, since it influences soil physical, chemical, biological properties and processes. It is a source of energy and nutrients for soil biota which affects the nutrient supplying capacity of soil *via* mineralization. It also affects aggregate stability, trafficability, water retention and hydraulic properties (Haynes, 2005). In addition to being a direct source of plant nutrients, SOM also indirectly influences the nutrient availability in soil. Besides, it is extremely important in maintaining overall quality of environment as soil contains significant part of global carbon stock (Lal *et al*., 1998).

Several studies (Cambardella and Elliott, 1992; Chan, 1997) suggest that certain fractions of soil organic matter are more important in maintaining soil quality and are therefore more sensitive indicators of the impact of management practices. Chan *et al*. (1998) reported decrease in soil organic carbon under agriculture land use in comparison to forestry and horticulture land uses. However, it is likely that both quantity and quality of soil organic carbon sequestered under different land uses are different, and these, in turn, can have different but important effects on soil quality such as soil structural stability and chemical fertility. This knowledge is important for the selection of suitable land use systems, either singly or as mixer, to moderate the impact of changing land use pattern on global climate change. Although soil organic matter includes a continuum of materials ranging from highly decomposable to very recalcitrant, it is divided into two major pools, labile and stabilized fractions for convenience (Haynes, 2005). The labile carbon pool is the fraction of SOC, which has rapid turnover rates and sensitive to alteration in land use management practices. The pool of SOC fuels the soil food web and therefore greatly influences the nutrient cycling for maintaining soil quality and its productivity. Cropping systems and management practices that ensure greater amount of crop residue to be returned to the soil are expected to cause a net build up of SOC stock (Majumder *et al*., 2008).

Most conventional methods used in soil organic carbon determination have been developed to maximize oxidation and recovery of C (Walkley and Black, 1934). However, total organic carbon measurements might not be sensitive indicators of changes in soil quality. Adoption of procedures that can extract the more labile fraction preferentially might be a more useful approach for characterization of soil organic carbon resulting from different management practices. To demonstrate the decline of a more labile form of organic carbon under cultivation, Blair *et al*. (1995) used potassium permanganate oxidizible organic carbon as a measure of soil organic carbon lability. Particulate organic carbon (POC) (Cambardella and Elliott, 1992) and soil microbial biomass carbon (SMBC) (Jenkinson and Powlson, 1976) are the other sensitive indicators for direct measurements of changes in SOM pools on short-term scale. SMBC is the fraction of the SOM that is actively involved in the transformation of soil organic residues and the dynamics of N, P and S in soil. Soil microbial biomass and its activity, especially sensitive to human activity, are suitable predictors of soil biological status in terms of soil fertility (Elliot *et al*., 1996).Thus, the improved quantification of C pools and fluxes in soil are important for understanding the contribution of the soils under different ecosystems to net C emissions and their potential for carbon sequestration. The potential of a land use for increased carbon sequestration capability can be assessed either through the amount of carbon stored or estimating the annual carbon sequestration rate (Iverson *et al*., 1993).

Carbon stock calculations

Total organic carbon and bulk density are used to calculate the carbon stocks. For total organic carbon, the method described by Snyder and Trofymow (1984) is used. Soil bulk density values in the fields are evaluated by the core method, using oven-dried soil mass and field volume of sample. Calcium carbonate estimation in the soils is carried out using HCl titrations. The inert carbon in the soil is computed using Falloon *et al.* (1998) equation given below.

$C_I = 0.049\ C_T^{1.139}$

Where, C_I is the inert carbon content (tha^{-1}), and C_T is total organic carbon in soil.

C stocks (Mg ha^{-1}) = C_{TOT} * BD * D

where, C_{TOT} is total organic carbon (g 100 g^{-1});

BD= Bulk density (g cm^{-3}) and D= Depth (cm)

Carbon Management Index (CMI)

Blair *et al*. (1995) proposed carbon management index (CMI), a multiplicative function of carbon pool index (CPI) and lability index (LI) as an indicator of the rate of change of soil organic matter in response to land management changes, relative to a more stable reference soil.

Non-labile carbon (C_{NL}) is calculated from the difference between total carbon (C_T), and labile carbon (C_L). The relative amounts of these two fractions and the total carbon in a cropped and reference soil have been used by Blair *et al*. (1995) to calculate a Carbon Management Index (CMI). This index compares the changes that occur in total and labile carbon as a result of agricultural practice, with an emphasis on the changes in labile carbon, as opposed to non-labile carbon in SOM. The CMI is calculated as follows:

a) Change in total C pool size

The loss of C from a soil with a large carbon pool is of less consequence than the loss of the same amount of C from a soil already depleted of C or which started with a smaller total C pool. Similarly, the more a soil has been depleted of carbon the more difficult it is to rehabilitate. To account for this, a Carbon Pool Index is calculated as follows:

$$\text{Carbon Pool Index} = \frac{\text{Sample total carbon (mg g}^{-1}\text{)}}{\text{Reference total carbon (mg g}^{-1}\text{)}} = \frac{C_T \text{ sample}}{C_T \text{ reference}}$$

b) The loss of labile C is of greater consequence than the loss of non-labile C. To account for this, since it is the turnover of labile carbon which releases nutrients and the labile carbon component of SOM appears to be of particular importance in affecting soil physical factors, a Carbon Lability Index is calculated as follows:

$$\text{Lability of Carbon } (C_L) = \frac{\text{C in fraction oxidized by KMnO}_4\text{ (mg labile C g}^{-1}\text{ soil)}}{\text{C remaining unoxidized by KMnO}_4\text{ (mg labile C g}^{-1}\text{ soil)}}$$

$$= \frac{C_L}{C_{NL}}$$

Lability of C in sample soil
Lability Index (LI) =
Lability of C in reference soil

c) The Carbon Management Index (CMI) is then calculated as follows:
Carbon Management Index (CMI) = C Pool Index * Lability Index *100
= CPI *LI * 100

Labile carbon

The amount of carbon oxidizable by 333 mM $KMnO_4$ (labile carbon) in soil is determined by following the procedure of Blair *et al.* (1995). For this purpose, 2.0 g of soil is taken in centrifuge tube and oxidized with 25 mL of 333 mM $KMnO_4$ by shaking in a mechanical shaker for 1 hour. The aliquots are centrifuged for 5 minutes at 4000 rpm and 1.0 mL of supernatant solution is taken in a conical flask, to which 250 mL of double distilled water (DDW) is added for dilution of the supernatant solution. The concentration of $KMnO_4$ is measured at 565 nm wavelength using spectrophotometer. The change in concentration of $KMnO_4$ is used to estimate the amount of carbon oxidized assuming that 1.0 mM of $KMnO_4$ is consumed (Mn VII – Mn IV) in the oxidation of 0.75 mM (9.0 mg) of carbon.

Microbial biomass carbon

Microbial biomass C (MBC) is determined by the chloroform fumigation incubation (CFI) technique as per the procedure of Jenkinson and Powlson (1976). 0.5 mm-sieved, shade-dried soil (10 g) is taken in a 50mL beaker in which 1.0mL of distilled water is added and is placed in an air-tight desiccator. Fumigation is carried out with ethanol-free chloroform by applying vacuum until the chloroform starts boiling. Close the tap of the desiccator and keep the desiccator in the dark for 5 days. After incubation, the soils are transferedinto 125mL extraction bottles, shaken with 0.5M.Potassium sulfate (K_2SO_4) for 30 minutes and filtered through (Whatman No. 42 or equivalent) filter paper. The MBC is then calculated from the net amount of total C (fumigated C and nonfumigated C) using a factor of 2.64 (Vance *et al*., 1987).

Total organic carbon

Total organic carbon in soil is determined by wet oxidation method (Synder and Trofymow, 1984). For this purpose, 1.0g of soil (passed through 1mm sieve) pretreated with 3.0 mL of 2 N HCl to remove carbonates is taken in a digesting tube, then oxidized with $K_2Cr_2O_7$ in presence of 25 mL of conc. H_2SO_4 and H_3PO_4 in a ratio of 3:2, by heating on digestion block for 2 hrs. Then, the evolved CO_2, trapped in 2 N NaOH, is measured by back titration with 0.5 N HCl using phenolphthalein indicator. Total organic carbon content is computed based on the amount of evolved CO_2.

Particulate and mineral-associated organic carbon

Particulate soil organic matter is a labile intermediate in the soil organic matter continuum from fresh organic materials to humified matter (Cambardella and Eliott, 1992). The isolation of SOM particulate from the mineral-associated fraction is performed by physical fractionation. The soil samples need to be air-dried, crushed with a wood roll and sieved (< 2 mm) and can be used for the estimation. 20 g of soil subsamples is placed in snap-cap flasks and dispersedwith 60 mL sodium hexametaphosphate $[(NaPO_3)_6]$ solution at 8.17 mmol L^{-1} (5 g L^{-1}) and shaken on horizontal shaker (60 cycles min^{-1}) for 15 hrs. Then, the suspension is poured on a 53 micron mesh and washed with distilled water to separate organic material from sand. The material retained in the sieve is considered as the particulate fraction and the material that passed through the sieve is considered as the mineral-associated fraction, which may be collected in a plastic bucket. Then, the particulate- associated fractions (both retained and passed fractions) are heated in an oven at 90 ºC in the first day and then at 50 ºC until it becomes completely dry. After drying and weighing, grind the particulate fraction samples with pestle and a mortar for C analysis. The carbon analysis can be done by the same procedure followed for total carbon analysis.

Extraction and characterization of soil organic matter

The soil samples are first equilibrated to a pH value between 1-2 with 1 M HCl at room temperature and the solution volume is adjusted with 0.1 M HCl to provide a final concentration that has the ratio of 10 mL liquid/1 g dry sample. The suspension is shaken for 1 hour and the supernatant is separated from the residue by decantation after allowing the solution to settle (or by low speed centrifugation). Neutralize the soil residue with 1 M NaOH to pH=7.0 and then add 0.1 M NaOH under an atmosphere of N_2 to give a final extractant to soil ratio of 10:1. Extract the suspension under N_2 with intermittent shaking for a minimum of 4 hours and allow the alkaline suspension to settle overnight and collect the supernatant by means of centrifugation. The supernatant is then acidified with 6 M HCl with constant stirring to pH=1.0 and then allow the suspension to stand for 12-16 hours. The humic acid (precipitate) and fulvic acid (supernatant - FA Extract 2) fractions are then separated by centrifugation.

The extracted humic acids must be purified for removing the impurities in it. This is done by first re-dissolving the humic acid fraction by adding a minimum volume of 0.1 M KOH under N_2. The solution is treated with solid KCl to attain 0.3 M (K^+) and then centrifuged at high speed to remove suspended solids. The supernatant is acidified with 6 M HCl with constant stirring to pH=1.0 so as to reprecipitate the humic acids. The supernatant is separated from the humic acid precipitate by centrifugation. The humic acid precipitate is suspended in 0.1 M HCl/0.3 M HF solution in a plastic container and is shaken overnight at room temperature. Centrifugation and HCl/HF treatment are to be repeated, if necessary, until the ash content is below 1 percent. The precipitate is then transferred to a Visking dialysis tube by slurring with water and dialyzed against distilled water until the dialysis water gives a nagative Cl^- test with the $AgNO_3$. Then, the humic acid need to be freeze-dried and can be used for estimation of carbon and nitrogen content, functional groups and E4/E6 ratio (Stevenson, 1994).

Forests, through growth of trees and an increase in soil carbon, contain a large part of the carbon stored on land. Forests present a significant global carbon stock. Global forest vegetation stores 283 Gt of carbon in its biomass, 38 Gt in dead wood and 317 Gt in soils (top 30 cm) and litter. The total carbon content of forest ecosystems has been estimated at 638 Gt for 2005, which is more than the amount of carbon in the entire atmosphere. This standing carbon is combined with a gross terrestrial uptake of carbon, which was estimated at 2.4 Gt a year, a good deal of which is sequestratered by forests. Most of the carbon stocks of croplands and grasslands are found in the below-ground plant organic matter and soil. Human activities, through land use, land-use change and forestry (LULUCF) activities affect changes in carbon stocks between the carbon pools of the terrestrial ecosystem and between the terrestrial ecosystem and the atmosphere. Management and/or conversion of land uses (e.g., forests, croplands and grazing lands) affect sources and sinks of CO_2, CH_4 and N_2O. According to the IPCC (2007), deforestation in the tropics and forest re-growth in temperate and boreal zones remained the major factors contributing to emissions and removals of greenhouse gases (GHG) during 1990s. CO_2 emissions associated with land-use change, averaged over the 1990s, were 0.5 to 2.7 Gt C yr^{-1}, with a central estimate of 1.6 Gt C yr^{-1}. Figure 1 reveals that conversion of agriculture land into forestry and horticulture plantation had increased the soil carbon stocks by 15 and 9%, respectively. It also signifies that even conversion of horticulture land use into forestry plantation increases SOC stocks by approximately 8%. Forest, horticulture and agriculture land uses recorded the SOC stocks of 287, 269 and 249 Mg ha^{-1}, respectively up to a depth of 75 cm in the soils of north-east regions of India (Ramesh, 2012). Irrespective of the land uses, the SOC stocks were higher in surface soils compared to subsurface soils. It implies the role of LULUCF activities in the mitigation of climate change either by increasing the removal of GHGs from the atmosphere or by reducing emissions by sources which can be relatively cost-effective. Labile carbon and MBC also followed the same trend as carbon stocks in all the land use systems i.e., Forestry>Horticulture>Agriculture (Fig 2). By converting the agriculture land to forestry plantations, labile and MBC content increased by 131 and 67%, respectively. Whereas, conversion of agricultural land use to horticulture land use registered 39 and 17% increase in both labile and MBC content, respectively.Ecosystems with high organic matter input and easily available organic matter compounds tend to have higher microbial biomass contents and activities because organic substances are the preferred energy source for the microorganisms (Hassink, 1994). The high concentration of detrital material in the surface soil layer (0–10 cm) in the subtropical forest increases the availability of soil organic matter in the surface layer due to fast turnover rates of litter and fine roots (Arunachalam *et al*., 1998). The chief contributory factor for the higher MBC and labile C in the forest land use than horticulture orchard and agriculture land use could be attributed to the greater availability of organic nutrients in the surface soils due to higher plant cover and quality of organic materials.

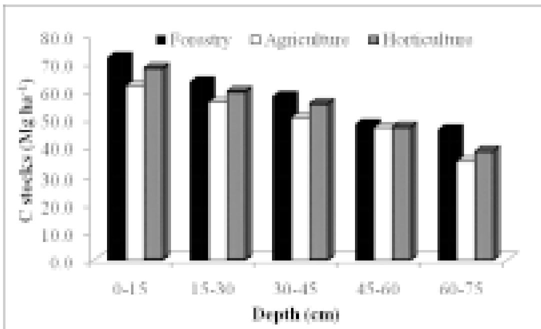

Fig1 Effect of different land uses and depths on carbon stocks (Mg ha^{-1})

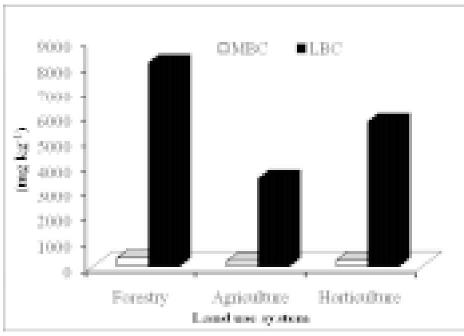

Fig 2 Effect of different land uses on soil microbial biomass carbon (MBC) and labile carbon (LBC)

Soil organic matter fractions with turnover times of years to decades, such as particulate organic matter (POM) or light fraction (LF), often respond more rapidly to management-induced changes in the SOC pool than more stabilised, mineral-associated fractions with longer turnover times (Six *et al*., 1999). Light fraction and POM are thought to represent partly decomposed plant material at an early stage of decomposition, thus characterising a transitional stage in the humification process.The effect of different land use systems on TOC and POC ranges from 2.49 to 3.14 and 0.22 to 0.47 g 100g^{-1}, respectively (Fig 3). Amongst the land uses, forestry plantation recorded the highest value of TOC and POC (3.14 and 0.47g 100g^{-1}) and the lowest was in agriculture land use (2.49 and 0.22 g100g^{-1}). Conversion of agriculture land use to forestry plantation increased the concentration of TOC and POC by 26 and 116%, respectively, whereas, conversion to horticulture plantation increased the concentration by 9 and 72%, respectively (Ramesh, 2012).

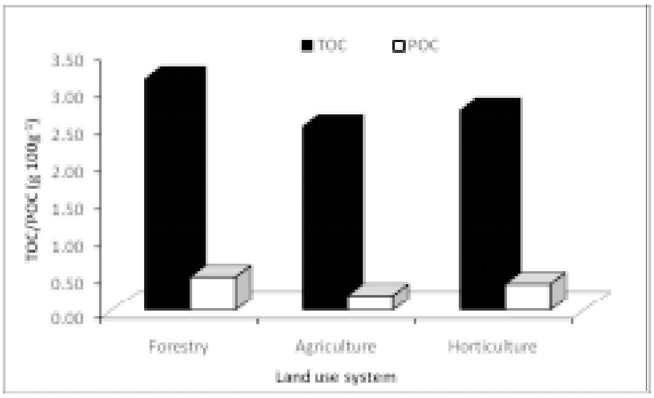

Fig 3 Effect of different land uses on soil total organic carbon (TOC) and particulate organic carbon (POC) (g 100g^{-1})

There are several management and land use practices which can act as sinks for the CO_2 and also contribute towards the productivity and profitability of the crops and cropping systems in north-east India. Some of them are: reduced tillage, use of cover crops, integrated nutrient management, mulching, soil and water conservation measures, tree plantations etc. Conversion of natural fallow into forest plantations, horticulture orchards, and agricultural land uses although increases the emission of CO_2 to atmosphere due to increased accumulation of SOC, it significantly increases the soil carbon stocks, fractions and quality which are important for the maintenance of soil health and long term productivity paving the way for mitigation of global warming. Accumulation of SOC under any land use systems depends on the quantity as well as quality of chemical composition (lignin/nitrogen ratio, carbon/nitrogen ratio, cellulose, hemi-cellulose etc.) of tree roots and litter and crop residues, and varies widely as a function of climate and soil type (Saha *et al*., 2007). The superiority of forestry land use in improving SOC stocks and fractions might be mainly due to higher fine root biomass and greater leaf fall of these tree species and quality litter production leading to improvement in C status of soil than the other land use systems (Geissen *et al*., 2009).

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Approaches for Greenhouse Gas Emission Studies from Rice Fields

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Introduction

Earth's climate is changing because of intense human activities that alter the chemical composition of the atmosphere through build-up of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The global atmospheric concentration of CO_2, CH_4 and N_2O increased from a preindustrial value of about 280 ppm to 387 ppm, 715 ppb to 1774 ppb and 270 ppb to 319 ppb, respectively (IPCC, 2007; IPCC, 2009). Global warming potential (GWP) of CH_4 and N_2O are 24.5 and 320 times greater than that of CO_2 (GWP of CO_2 = 1) for a 100 year time horizon (IPCC, 2007). The natural as well as anthropogenic activities have serious effects on the GHGs emissions that include ever increasing concentrations of CO_2, CH_4 and N_2O in the atmosphere. The heat-trapping properties of these GHGs are well established. GHGs differ in their warming influence (radiative forcing) on the global climate system due to their different radiative properties and lifetimes in the atmosphere. Changes in the atmospheric concentrations of GHGs alter the energy balance of the climate system which leads to subsequent climate change. They affect the absorption, scattering and emission of radiation within the atmosphere and at the earth's surface. The resulting positive or negative changes in energy balance due to these factors, known as radiative forcing, is used for comparison of warming or cooling influences on global climate. Atmospheric concentrations of GHGs increase when emissions are larger than removal processes. These GHGs have profound impact on global climatic changes resulting in increase in ambient temperature which is likely to affect agriculture. It is anticipated that increasing concentrations of GHGs are likely to accelerate the rate of climate change further. Scientists are expecting that the average global surface temperature could rise by 1.4°C – 5.8°C by 2100 AD with significant regional variations (IPCC, 2007).

Agriculture is also one of the anthropogenic sources of atmospheric GHGs. Its prime objective is to providing food for rapidly increasing world population. But at the same time, it is also causing damage to the environment as exemplified by the global rise in the concentrations of CO_2, CH_4 and N_2O from agriculture sector. CO_2 is the most important anthropogenic GHGs and mostly originate from industrial activities, deforestation, burning of fossil fuels, land use changes and microbial decomposition of soil organic matter. But, CO_2 has a significant impact on crop photosynthesis, agricultural production and productivity. On the other hand, the increase in CH_4 concentration is predominantly due to agriculture (flooded rice paddies), animal husbandry, landfills, wetlands and fossil fuel use while the increase in N_2O is primarily due to agriculture, produced in considerable amounts both in upland (aerobic) and submerged (predominantly anaerobic) soils especially under intensive N-fertilizer dependent agriculture. Rice cultivation is considered as one of the most important anthropogenic sources of CH_4. Rice is the most important cereal for the majority of Indian population, and rice and rice-based cropping systems are the backbone of Indian agriculture. But, for providing food to rapidly increasing population it is also causing damage to the environment by becoming a source of GHGs. However, flooded rice fields can act both as source and sink of GHGs depending on the cultivation processes, agricultural operation and management practices. Strategies to reduce the emissions must focus on reducing their production, increasing their consumption and reducing their transport through plants. Thus, present and future researches should aim at providing technologies for monitoring, characterization, budgeting (quantification) and mitigation of emissions of major GHGs from rice and rice-based cropping systems keeping in mind the sustainable agricultural productivity. These technologies, if properly adopted, would substantially cut down GHGs emissions from rice and rice-based production systems.

Technologies for monitoring greenhouse gas emissions from rice fields

Agricultural fields (flooded and aerobic rice production) have important roles on greenhouse gas budget. The rice crops uptake atmospheric CO_2 due to photosynthesis; the soil microorganisms along with crop emit CO_2 during respiration. Lowland submerged paddies are major CH_4 sources and upland conditions enriched with nitrogenous fertilizers mostly emit N_2O and CO_2. These sink/source strength capacity depends on the management practices. Therefore, greenhouse gas emission from rice fields (different rice production systems) demand continuous, precise and accurate monitoring and their proper quantification for budgeting. Several technologies are available for monitoring greenhouse gas emissions from agriculture. Real time, accurate and precise monitoring of GHGs emissions from rice paddy ecosystems are possible with the help of open/closed path eddy covariance (EC) technique-based estimations of net ecosystem CO_2 exchange (NEE), EC technique-based automated measurement of CH_4 and N_2O, high frequency closed manual/automatic chamber measurements of CH_4, N_2O and soil/plant respiration by soil plant (canopy) respiration chambers.

Eddy covariance technique-based net ecosystem carbon dioxide exchange (NEE)

Long-term measurements of CO_2 flux have been carried out in various ecosystems in the world, especially in forest ecosystems as they are believed to be the most influential terrestrial ecosystems in the global CO_2 budget (Saigusa *et al*., 2002; Carrara *et al*., 2003).

Fig 1 EC system

On the other hand, non-forest ecosystems *viz*., grasslands, wetlands and agricultural fields had also been observed because they contribute to regional and global CO_2 budgets (Saito *et al*., 2005; Tsai *et al*., 2006). The EC technique (Fig 1) is widely employed as the standard micrometeorological method to monitor fluxes of CO_2, water vapour and heat, which are bases to determine CO_2 and heat balances of land surfaces (Aubinet *et al*., 2000). The EC technique has become the most important method for measuring trace gas exchange between terrestrial ecosystems and the atmosphere (Baldocchi, 2003; Smith *et al*., 2010). The direct, continuous measurement of carbon, water and energy fluxes between vegetated canopies or biosphere and the atmosphere can be obtained with minimal disturbance to the vegetation using this sophisticated research tool. It can represent a large area of land at the ecosystem than the typical plot area (Papale *et al*., 2006; Desai *et al*., 2008; Lalrammawia and Paliwal, 2010) for short period to very long periods spanning over several years. It has become the backbone for bottom up estimates of continental carbon balance from hourly to inter annual time scales (Papale and Valentini, 2002; Reichstein *et al*., 2005).

In Asia, EC flux measurements were conducted in Japan (Miyata *et al*., 2000; Miyata *et al*., 2005; Saito *et al*., 2005), Korea (Moon *et al*., 2003), Bangladesh (Hossen *et al*., 2007; Hossen *et al*., 2011), the Philippines (Alberto *et al*., 2009), Thailand (Pakoktom *et al*., 2009), China (XiuE *et al*., 2007) and Taiwan (Tseng *et al*., 2010) to monitor seasonal, annual and/or inter-annual variations in CO_2 fluxes in rice fields. In rice paddy ecosystems it can be employed to measure net ecosystem CO_2 exchange (NEE) or net ecosystem production (NEP). The technique uses the covariance between rapid fluctuations in vertical wind speed measured with a three-dimensional ultrasonic anemometer and simultaneous measurements of the rapid fluctuations in the CO_2 concentration which is measured by a fast-response infrared gas analyzer (IRGA). A positive covariance between vertical fluctuations and the CO_2 mixing ratio indicates the net CO_2 transfer into the atmosphere from plant-soil system and a negative value indicates net CO_2 absorption by the vegetation (Moncrieff *et al*., 1997).

NEE is measured continuously by EC technique applying proper correction terms and gap-filling, if required. NEE is further partitioned into gross primary production (GPP) and ecosystem respiration (RE). RE is extrapolated from night time fluxes to daytime by using temperature response functions and afterwards GPP is calculated (Fig 2) by subtracting RE from NEE (Smith *et al*., 2010).

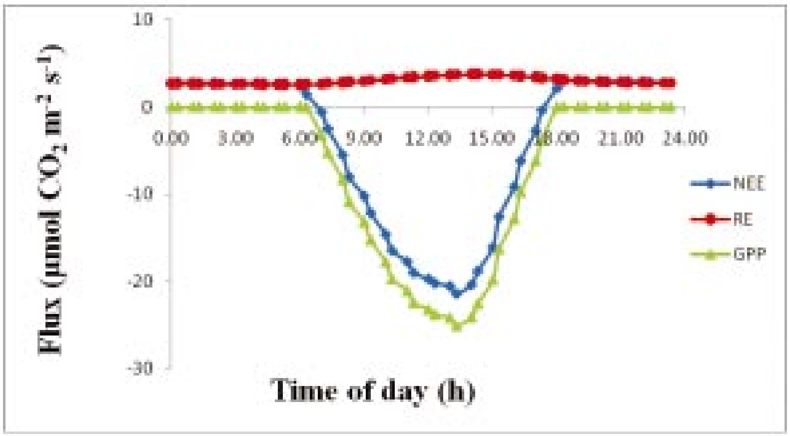

Fig 2 NEE, GPP and RE

Measurement of soil respiration (soil CO_2 efflux) and plant respiration by infra-red gas analyzer (IRGA)-based soil respiration chamber

The most important processes affecting carbon balance of a terrestrial ecosystem are photosynthesis of above-ground vegetation and soil respiration. The relationship between production and decomposition determines whether a system is a sink or a source of atmospheric CO_2 (Pumpanen *et al*., 2004). Therefore, accurate assessment of soil respiration is crucial for understanding and predicting ecosystem responses to anthropogenic perturbations *viz*., climate change, pollution and agriculture. Soil respiration is the major pathway of C efflux from terrestrial systems and represents an integrated reporter of ecosystem functioning (Mills *et al*., 2011). Reducing CO_2 emissions from soils may help to increase sequestration of atmospheric CO_2 in soil. Soil respiration includes root and microbial respiration, and bulk turnover of organic matter (OM) which all contribute to the release of CO_2 (Hill *et al*., 2004). Soil respiration seems to be one of the primary fluxes of C between soils and the atmosphere, with a global release of 75 Pg C $year^{-1}$ (Iqbal *et al*., 2009). Infra-red gas analyzer (IRGA)-based field measurement is the most widely used technique for assessing soil respiration flux rates (Fig. 3). The method (for measuring soil CO_2 efflux employing infra-red gas analyzer) estimates the increase CO_2 concentration in an enclosed chamber over a specified time (Luo and Zhou, 2006). Different IRGA-based measurements of soil respiration / soil CO_2 efflux depends on differences in IRGA and chamber design (cuvette area and volume, use of collars, presence or absence of chamber vents), measurement parameters (enclosure time, chamber flow rate, purge parameters) and CO_2-flux algorithms (with or without moisture and temperature correction). These effects are also dependent on soil type and vegetation in which the measurements are taken (Mills *et al*., 2011). Moreover, the chambers always affect the object being measured, with each chamber type having its own limitations (Davidson *et al*., 2002).

Fig 3 Soil respiration chamber in rice field

Measurement of CH_4 and N_2O fluxes by chamber method

CH_4 and N_2O emissions are also measured through the manual/automatic closed chamber measurements. These chamber measurements are widely used as they are easy to apply in field trials with multiple small plots. The manual chamber measurements (Fig 4) are usually made very frequently (2-3 days interval) whereas automatic chamber measurements allow continuous and frequent measurements.

From the static chambers (equipped with small pulse pump for homogeneous mixing of air sample inside the chamber over specific time period) air samples are collected in tedlar® bags at 0, 15 and 30 minute intervals. Samples are then collected by syringe for analysis of CH_4 and N_2O by gas chromatography using flame ionisation and electron capture detectors, respectively (Adhya *et al*., 1994; Das *et al*., 2011).

Quantification of net ecosystem exchange of CO_2 (NEE), ecosystem respiration (RE) and gross primary production (GPP)

Seasonal variation in ecosystem CO_2 exchange with the atmosphere occurs in response to meteorological conditions and physiological activities of rice crop. The net ecosystem exchange (NEE) of CO_2 between the biosphere and the atmosphere is the balance between fluxes associated with photosynthetic assimilation by the foliage (Gross ecosystem production, GEP) and respiratory effluxes from autotrophs (roots) and heterotrophs (microbial and soil fauna). In rice based cropping system in Asia, a number of studies with eddy covariance (EC) flux measurements were conducted and some of them are discussed below:

Fig 4 Chamber measurement of CH_4 and N_2O emission

At IRRI, the Philippines, throughout the study period, NEE was negative during the daytime and positive during the night time for both flooded and aerobic rice fields (Alberto *et al*., 2009). From active tillering to panicle initiation stage, NEE was about -10 µmol CO_2 m^{-2} s^{-1} and it reached as low as its lowest value of -22 µmol CO_2 m^{-2} s^{-1} during heading to flowering stage in flooded rice fields. From tillering to ripening stage, the flooded rice fields behaved as net CO_2 sink on a daily basis and maximum uptake was noticed during heading to flowering stage and the value obtained was -5.98 g C m^{-2} day^{-1}. Aerobic rice fields became net sink for CO_2 at reproductive stage and continued to behave as net CO_2 sink at harvest stage with the mean value of -2.31 g C m^{-2} day^{-1}. The total C budget integrated over the cropping period showed that in flooded rice fields, NEE (-258 g C m^{-2}) was about three times higher than the NEE (-85 g C m^{-2}) of aerobic rice fields. The gross primary production (GPP) and ecosystem respiration (RE) values for flooded rice fields were 778 and 521 g C m^{-2} and in case of aerobic rice fields, the values of GPP and RE were 515 and 430 g C m^{-2}, respectively.

CO_2 emission in a subtropical red paddy soil of southern China was measured by static closed chamber technique and was analyzed with a portable infra-red analyzer (Iqbal *et al*., 2009). CO_2 flux was measured during the growth stages of rice from row, inter-row and bare soil. Soil CO_2 fluxes from row (797-1214 g C m^{-2} $season^{-1}$) were significantly higher than that of inter-row (289-403 g C m^{-2} $season^{-1}$) and bare soil (148-241 g C m^{-2} $season^{-1}$).

Monitoring and quantification of CH_4 emission from rice fields using chamber measurement technique

Methane emission in rice fields is affected by the properties, structure and dynamics of the submerged soil. CH_4 emission increases under continuous flooding in rice fields and it escapes to the atmosphere through the aerenchyma of the rice plant. Methane emission shows pronounced variations among the rice growing sites of the world, even under identical crop management conditions. Continuous flooding, pure mineral fertilizer and cultivar types have significant influence on CH_4 emission.

At Central Rice Research Institute (CRRI), Cuttack, an irrigated continuously flooded rice paddy showed a CH_4 flux value of 4-26 mg m^{-2} hr^{-1} and 0.7-4.7 Gg ha^{-1} per cropping season of 75 days (Adhya *et al*., 1994). Adhya *et al*. (2000) reported average methane emission of 32 kg ha^{-1} yr^{-1} from a rainfed tropical rice ecosystem of CRRI, Cuttack and Jain *et al*. (2000) reported CH_4 emission of 23.0 kg ha^{-1} from irrigated rice-wheat cropping system of IARI, New Delhi, India.

Experiments were conducted to determine the effect of fertilizer management practices on methane emission from a rainfed lowland rice field (water depth about 3–30 cm) and an irrigated shallow rice field (4–6 cm), both planted with the same cultivar, cv. Gayatri. Methane emission peaked from 100 to 125 days after transplanting followed by a decline in rainfed lowland field plots. Application of prilled urea did not enhance methane emission significantly over that of the untreated control. Subsurface application of urea super granules was effective in reducing the methane flux over that of the control. Methane emission was lowest in plots treated with the mixture of prilled urea and Nimin (a nitrification inhibitor). Under irrigated shallow conditions, the application of prilled urea and green manure (*Sesbania rostrata*) singly, and in combination, significantly increased methane emission over that of the control.

Cumulative methane efflux from control and prilled urea treated lowland rice field was about 4–10 times higher than that in irrigated shallow fields. The cumulative methane efflux from irrigated shallow field plots planted with cv. Gayatri was in the order of control (38.8 g m^{-2}) < green manure (70.0 g m^{-2}) < prilled urea (73.8 g m^{-2}) < prilled urea + green manure (116.3 g m^{-2}); and from rainfed lowland field plots planted with cv. Gayatri it was prilled urea + Nimin (255.0 g m^{-2}) < urea super granule (295.0 g m^{-2}) < prilled urea (307.5 g m^{-2}) < control (347.5 g m^{-2}) (Rath *et al*., 1999).

Influence of application of *Azolla* (*A. caroliniana* Wild.), a widely used bio fertilizer for rice (*Oryza sativa* L.), on CH_4 efflux from a flooded alluvial soil planted with rice were investigated in a field experiment at Cuttack, India. *Azolla* was either incorporated as green manure at the beginning of the experiment or grown as dual crop in the standing water along with the rice crop. Dual cropping of *Azolla* (equivalent to 30 kg N ha^{-1}) in conjunction with urea (30 kg N ha^{-1}) resulted in lowest CH_4 flux (89.29 kg CH_4 ha^{-1}). Cumulative CH_4 flux followed the order of urea (155.28 kg ha^{-1}) > *Azolla* (incorporated) + urea (149.37 kg ha^{-1}) > *Azolla* (incorporated + dual crop) (105.64 kg ha^{-1}) > no N control (94.94 kg ha^{-1}) > urea + *Azolla* (dual crop) (89.29 kg ha^{-1}). The mean CH_4 emission followed the order of urea at 60 kg N ha^{-1} (8.15 mg CH_4 m^{-2} h^{-1}) > *Azolla* (incorporated) + urea at 30 kg N ha^{-1} (7.80 mg CH_4 m^{-2} h^{-1}) > no N control (5.80 mg CH_4 m^{-2} h^{-1}) > *Azolla* (incorporated + dual crop) (5.40 mg CH_4 m^{-2} h^{-1}) > *Azolla* (dual crop) + urea at 30 kg N ha^{-1} (4.61 mg CH_4 m^{-2} h^{-1}) (Bharati *et al*., 2000).

CH_4 emission was studied in rice-fish farming system under deep water rice ecology. The mean CH_4 emission (mg CH_4 m^{-2} h^{-1}) from sowing to harvest followed the order: Varshadhan + fish (2.52) > Durga + fish (2.48) > Durga (1.47) > Varshadhan (1.17). Cumulative CH_4 emission was highest in the treatment Varshadhan + fish (96.33 kg ha^{-1}) while the lowest emission was recorded in field plots planted with cv. Varshadhan without fish (45.38 kg ha^{-1}). The percentage increase in CH_4 emission as a result of fish rearing was 112 in case of cv. Varshadhan and 74 in case of cv. Durga (Datta *et al*., 2009).

Monitoring and quantification of N_2O emission from rice fields using chamber measurement technique

N_2O budget of rice field is affected both by the structure and dynamics of anaerobic/aerobic conditions in the soil. N_2O is primarily emitted in pulses after fertilization, flooding the field and due to high rainfall. N_2O predominantly escapes to the atmosphere through the aerenchyma of the rice plant. The morphology of the aerenchyma allows the re-construction of the vertical gas transfer including the speed-limiting passage from root to culm. Nutrient supply affects development of aerenchyma as well as root exudation and thus budget of N_2O. On an average, N_2O accounts for approximately 5% of the total green house effect. It also plays an important role in the destruction of the stratospheric ozone, which protects the earth from ultra-violet radiation from the sun. Soil is considered to be one of the major contributors with 65% of the total global emission. Various soil, climate and management factors *viz*., soil moisture regime, temperature, pH, N-content of soil, soil organic carbon and presence of crops control the N_2O emission from agriculture fields. N_2O emission from irrigated and upland paddy fields of India was estimated 4-210 and 2-10 Gg year^{-1}, respectively. N_2O emission from Indian agricultural field was estimated to be 0.08 Tg annually. Potassium nitrate applied paddy soil emitted more amount of N_2O as compared to ammonium sulphate treated plot (Pathak, 1999).

N_2O emission was studied in rice-fish farming system under deep water rice ecology at CRRI, Cuttack. Mean N_2O emission (µg N_2O m^{-2} hr^{-1}) from sowing to harvest followed the order: rice cv. Varshadhan (without fish) (36.92) > rice cv. Durga (without fish) (31.33) > Varshadhan + Fish (29.77) > Durga + Fish (29.57). Extending the mean emission fluxes to cumulative values (kg N_2O ha^{-1}), N_2O emission followed the order of Varshadhan (without fish) (1.02) > Durga (without fish) (0.92) > Varshadhan + Fish (0.75) > Durga + Fish (0.72) (Datta *et al*., 2009).

N_2O emission from rice fields was affected by herbicide application. A field experiment was conducted to investigate the impacts of separate and combined applications of herbicides, bensulfuron methyl and pretilachlor on the emission of N_2O in a flooded alluvial field planted with rice cv. Lalat. Single application of both the herbicides resulted in significant reduction of N_2O emission while combination of these two herbicides distinctly increased N_2O emissions. Cumulative N_2O emissions (kg N_2O-N) followed the order of bensulfuron methyl (0.35 kg ha^{-1}) < pretilachlor (0.36 kg ha^{-1}) < control (0.45 kg ha^{-1}) < bensulfuron methyl 0.6% + pretilachlor 6% single dose (0.49 kg ha^{-1}) < bensulfuron methyl 0.6% + pretilachlor 6% double dose (0.54 kg ha^{-1}) (Das *et al*., 2011).

Mitigating greenhouse gas emissions from rice fields

The emissions of GHGs like CO_2, CH_4 and N_2O from the rice fields to atmosphere are controlled by several factors *viz*., their production, consumption, transport processes through plants, rice varieties, soil types, fertilizer application practices and agricultural operations.

CH_4 emission from flooded rice paddy ecology is influenced by the organic amendment, water and fertilizer management and rice cultivars whereas N_2O production is more influenced by soil factors and application of nitrogenous fertilizers.

The different mitigation options for reducing CH_4 and N_2O emission from rice fields are

i) Judicious water management
ii) Identification of proper rice cultivars
iii) Efficient fertilizer management
iv) Use of nitrification inhibitor
v) Manipulation of cropping practices
vi) Effective land management

Under the prevailing wetland conditions in rice field, farmers have options to reduce methane emission through distinct drainage period in mid season or alternate wetting and drying of soils as under tropical rainfed conditions. Selection of rice cultivars plays an important role in determining the quantity of methane emission from a given ecosystem. Results from various studies indicated the varietal variations with respect to quantities of methane emissions. In rainfed lowland rice, deep placement of urea super granules reduced both CH_4 and N_2O emissions as compared to prilled urea broadcasting. Phosphorus applied as SSP or rock phosphate distinctly inhibited CH_4 production or its emission from flooded rice fields. The supply of K through K_2SO_4 also reduced CH_4 emission. Organic nitrification inhibitors like Nimin and Karanj oil have shown to inhibit N_2O emission from flooded alluvial soils planted with rice. Cultural practices such as direct seeding vs. transplanting, close planting vs wide planting, rationing, weeding have effect on methane emission. Land management in the winter season significantly affected methane emission and soil redox potential during the following flooded period of rice cultivation. Rice straw and green manure application at an appropriate time prevent large amounts of CH_4 being emitted to the atmosphere.

Conclusion

Research efforts during last three decades have enhanced our understanding on the process involved in soil organic carbon sequestration and intensity of GHG emission under different environmental and agronomic situations. This has resulted in generation of information leading to refinement of the national inventories for GHGs, soil organic carbon sequestration potential in rice-paddies, GHG fluxes between rice fields and the atmosphere which are controlled by several biological and physical processes. As many of the factors controlling gas exchange between rice field and atmosphere are different in different ecosystems, field studies should be designed to measure net fluxes and to improve understanding of the factors including detailed mechanisms controlling the fluxes in different rice production systems. The eddy covariance technique measures directly the net ecosystem CO_2 exchange for characterization of carbon budget in terrestrial ecosystems. This device when coupled with other accessory sensors and trace gas analyzers can measure CH_4 and N_2O fluxes from rice fields. Quantification of net fluxes of CO_2, CH_4 and N_2O exchanged between the rice fields and atmosphere is required for budgeting of GHGs and to determine their impact on vegetation. Impact of greenhouse gases on climatic conditions and the influence of such climatic change on rice productivity is now a reality, although there is a need to assess the extent of such influences.

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Soil Organic Carbon Fractions and their Management

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Introduction

Soil is a dynamic, living, natural body that is vital to the function of terrestrial ecosystems and represents a balance among physical, chemical and biological factors. Soil organic carbon (SOC) is the key component of soil organic matter (SOM) and is the central element of soil as decline in SOM is considered to create an array of negative effects on crop productivity. Maintaining and improving SOM or SOC is pre-requisite to ensuring soil quality, future productivity, and sustainability of agriculture (Katyal *et al*., 2001). SOM is not only important for sustainability of agricultural ecosystems, but also extremely important in maintaining overall quality of environment as soil contains a significant part of the global carbon stock. The SOM is an important attribute of soil quality and soil health, since it influences soil physical, chemical, biological properties and processes. Being a direct source of plant nutrients, SOM also indirectly influences nutrient availability in soil. There is a growing interest in assessing the role of soil as a sink for carbon under different agricultural management practices and land uses, because some estimates show that increase in SOC content by 0.01% could lead to C-sequestration equal to the annual increase of atmospheric CO_2-C (Lal *et al*., 1998).

Soil organic carbon fractions

Soil organic carbon includes a continuum of materials ranging from highly decomposable to very recalcitrant fractions. However for convenience, it is divided into two major pools, such as labile and stabilized fractions. Stabilized organic carbon is composed of organic materials that are highly resistant to microbial decomposition, which are complex materials of high molecular weight organic molecules made up of phenolic polymers produced from the products of biological degradation of plant and animal residues and the synthetic activity of microorganisms (Baldock and Nelson, 2000). On the other hand, the labile fractions consist of materials in transition between fresh plant residues and stabilized organic matter (Haynes, 2005). These fractions of soil organic carbon have a short turn over time usually less than 10 years. Stabilized organic carbon is generally measured in terms of total organic carbon content and this organic fraction of soil typically accounts for small but variable proportions (usually 5-10%) of soil mass. Over the years, two basic approaches have been used to quantify total carbon (organic + inorganic) in soil, *viz*., dry and wet combustion (Page *et al*., 1982). Generally total organic carbon in soil is determined by combustion after removal of inorganic carbon. As both of these procedures are cumbersome and time consuming, e estimation of soil organic carbon either for agricultural sustainability or environmental quality have been done in most of the studies by Wakley and Black method (Wakley and Black, 1934). Another simpler approach for approximation of total organic carbon in soils is through determine the loss of soil mass on ignition (Rowell, 1994).

Labile fractions of organic carbon were differentiated and separated in different forms based on the different chemical reagents or extractants. Loginow *et al*. (1987) used 33, 167 and 333 mM $KMnO_4$ to oxidize increasing proportions of the soil carbon within a fixed time interval to characterize the lability of soil carbon based on the ease of oxidation. Subsequently, several studies indicated that use of a single strength of $KMnO_4$ provided sufficient and reasonable characteristics of labile carbon to define the state of soil system. Soil organic carbon oxidized by 333 mM $KMnO_4$ has been considered as a useful index of labile soil carbon (Blair *et al*., 1995). This fraction encompasses all readily oxidizable organic components including humic materials and polysaccharides. Generally, this fraction accounts for 5-30% of organic carbon present in soils (Blair *et al*., 1995). Different studies indicated that this fraction of carbon is more sensitive to the changes in cultivation or agricultural management practices compared to total SOC (Blair, 2000). Over the years, numerous other extractants have also been used to characterize the labile fractions of SOM such as hot water, 0.1 M $CaCl_2$, 2 M KCl, alkaline permanganate, sodium chromate ($Na_2CrO_4 + H_3PO_4$), 6 *N* H_2SO_4, $K_2Cr_2O_7 + H_2SO_4$, sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), sodium pyrophosphate ($Na_2P_4O_7$), acetyl acetone, acetyl aldehyde acetate, chelating resin etc. (Haynes, 2005). Out of these, hot water extractable and dilute acid hydrolyzable carbon has been used recently to evaluate the labile organic matter for soil quality evaluation. Hot water extractable carbon accounts for about 1-5% of soil organic carbon (Chan and Heenan, 1999). Ghani *et al*. (2000) observed that 45-60% of carbon extracted with hot water is carbohydrate and several others have suggested that organic substances in hot water extract are mainly of microbial origin (Redl *et al*., 1990). Dilute acid hydrolyzable carbon in soil is extracted by 0.5-2.5 M H_2SO_4which mainly consists of carbohydrate carbon (Shepherd *et al*., 2001). This fraction of carbon was reported to be 32-45% of total soil organic carbon depending upon strength of acid and soil condition. The microbial biomass carbon mainly consists of bacteria and fungi and makes up about 1-5% of total soil organic carbon (Haynes, 2005) and is considered as the agent of biochemical changes in soil. A transitory pool of organic matter between fresh plant residues and humified organic carbon has been termed as particulate organic matter (Gregorich and Janzen, 1996). This fraction is composed primarily of plant debris with a recognizable cellular structure, but microscopic examination has revealed that it also contains fungal hyphae, spores, seeds, faunal skeleton etc. (Skjemstad *et al.,* 1990). Although this fraction of organic matter represents only a small portion of soil mass, its short turn-over time makes it an important source of carbon and nutrients. Particulate soil organic matter (PSOM) can be fractionated into light (LF) and sand size fractions (SSF) by dispersing soil materials on highly dense liquid typically between 1.5 and 2.0 g cm^{-3} density and subsequent sieving (Gregorich and Ellert, 1993). Sand size fraction carbon generally represents a much higher proportion of carbon than light fraction (LF) carbon particularly in agricultural soils, which is more decomposed. In agricultural soils, the LF and SSF make up 2-18% and 22-45% of total organic carbon, respectively (Carter *et al*., 1998). Dissolved organic matter (DOM) is the organic material present in dissolved form in soil solution. In very recent times, it has been used as a labile organic matter fraction and soil quality indicator in agricultural soil (Haynes, 2005). It originates as leachates from plant litter, exudates from soil microflora and roots, and hydrolysis of insoluble soil organic matter. This fraction of organic carbon in field-moist-soil typically accounts for 0.05 to 0.4% and 0.25 to 2% of total organic carbon in agricultural and forest soils, respectively (Smolander *et al*., 2001).

Soil organic carbon fractions affected by land uses and agricultural management practices

An adequate amount of soil organic matter is considered essential for long-term sustainable agriculture, because its decline decreases crop productivity. Changing soil organic matter levels may also alter the capacity of soil to act as a sink for atmospheric carbon dioixide (CO_2) and affect the global carbon balance. The quantity and quality of soil organic carbon as influenced by different management practices and land uses.

The most dramatic changes in soil organic carbon occur by conversion of land under natural vegetation (e.g., forest, pasture etc.) to arable agriculture (Kern and Johnson, 1993). Typically, organic matter level declines rapidly in the first few years and then stabilizes at a new equilibrium level after 30-100 years (Paustian *et al*., 1997). A number of factors contribute to the buildup or losses of organic carbon under arable agriculture, such as tillage intensity, addition of manures and fertilizers, crop rotation and climate (Zeilke and Christenson, 1986; Potter *et al*., 1998; Peterson *et al*., 1998; Katyal *et al*., 2001). However, changes in soil management practices and landuses within agricultural systems usually bring too subtle change in total organic carbon content in soil to be measured on short-term basis because of the relatively large variability in background organic matter. Such changes are usually demonstrated in long-term experiments (Gajri *et al*., 2006). Organic matter losses from soil following cultivation of native ecosystem have been reported since the early part of the 20th Century. Generally soil cultivation stimulates soil carbon loss because it accelerates oxidation of soil C by microbial activity (Peterson *et al*., 1998). The decrease in soil organic carbon is not only a function of the lower productivity of agro-ecosystem compared to the natural vegetation, but also because of the fact that most of the primary production is removed by harvesting, burning and animal feeding.

Tillage is one of the most important agricultural management practices that affect carbon level in soils. The most common method to reduce the rate of organic matter decomposition is to create less disruption to soil by shifting from conventional to minimum or zero tillage. Generally organic matter content in the surface soil of no till practices is greater than that of tilled soil (Peterson *et al*., 1998). The losses of organic matter in tilled soils occur due to aggregate disruption and exposure of physically protected organic matter to microbial action that enhances decomposition rates. Lal *et al*. (1999) observed that elimination of conventional system and subsequent adoption of a no tillage system over 25-50 years resulted in 50-75% recovery of organic carbon. Considering the different fractions of soil organic carbon, Greogrich *et al*. (1997) suggested that labile pools can be used as early indicators of changes in total organic matter that will become more obvious in the longer-term. Alvarez *et al*. (1995) reported that under the no till and chisel tillage for 12 years, the microbial biomass carbon level of 0-5 cm soil layer of Typic Argiudoll was about twice that under ploughed tillage. Buildup in labile form of organic matter under no till system was ascribed to a decrease in mineralization intensity of soil organic matter in no tilled plots than tilled ones. Although few studies (Verma *et al.*, 2010) were conducted to assess the impact of conversion of native ecosystem into arable land on labile pool ($KMnO_4$ oxidizable carbon) of soil organic carbon, information specific to tillage management is very little. Application of manures and fertilizers at optimum rates increase the crop production which in turn results in greater residue inputs leading to enhanced buildup of carbon in soil (Rasmussen *et al*., 1998). The magnitude of the benefits however depends upon indigenous fertility of soil and climatic conditions. Even single application of manure, if applied at higher rate, can result in measurable enhancement in soil organic carbon and generally linear changes in soil organic carbon occurs with increasing residue addition to soil (Rasmussen and Albrecht, 1998). Long term fertilizer trials clearly demonstrated that balanced fertilization (N, P and K) enhanced the soil organic carbon content (Gajri *et al*., 2006). However, application of FYM along with recommended dose of N, P and K could enhance or maintain the initial level of soil organic carbon in all the soils. Apart from these long-term fertilizer trials, several other studies also indicated that application of FYM, green manure, crop residues, biofertilizers and other wastes along with inorganic fertilizers enhanced the organic carbon and other plant nutrient contents in soils (Sarkar *et al*., 1998; Anand-Swarup and Yaduvanshi, 2000; Goswami and Rattan, 2000). Labile pools of soil organic carbon are more vulnerable to the changes in to manuring and fertilization in arable lands. Soil management practices have variable effects on soil microbial biomass carbon; it was reported that addition of fertilizer nitrogen decreased microbial biomass carbon (MBC) in pine forest, pasture and grasslands (Bristow and Jarvis, 1991); on the contrary, other studies have shown an increase in MBC in agricultural soils (Hesebe *et al*., 1985). Crop management systems that increase carbon input by applying green manures, crop rotations or addition of organic wastes have been shown to increase microbial biomass and activity than systems that rely on fertilizer inputs only. Graham *et al*. (2002) that reported greater inputs of organic matter due to either increased return of above-ground crop residues or increased deposition due to higher yields (induced by annual fertilizer application) caused a proportionately greater increase in MBC. Limited information is available on the influence of cultivation and agricultural management practices on $KMnO_4$–oxidizable labile pool of C (LBC). In the surface soil (0-5 cm), LBC content increased significantly in response to increasing amount of crop residues being returned and annual NPK fertilizers added under long-term trials. All these studies are univocal that labile pools of carbon are more sensitive to changes in land-uses or agricultural management practices. Although the responsiveness of dissolved organic matter to changes in agricultural management practices is not well documented, nevertheless, in a few studies, it has been shown to be altered more markedly than organic carbon in response to addition of crop residues, conversion of conventional practices to organic systems, conversion of arable system to pasture, change in crop rotation and addition of fertilizers (Haynes, 2000; Graham *et al*., 2002).

Agricultural sector in this country has been a major user of water and share of water allocated to irrigation is likely to decrease by 10-15% by the next two decades (CWC, 2000). Consequently, the use of domestic and industrial waste waters for irrigating crops may increase. In India, most of the raw sewage is a mixture of domestic, commercial and industrial activities and usually carry higher load of organic matter (Chhonkar *et al*., 2000; Rattan *et al*., 2002). Consequently, the long-term use of sludge or such waste waters on agricultural land resulted in considerable buildup of organic carbon in soils. On the other hand, increasing disposal of sewage, sludge, industrial by-products and municipal wastes on agricultural land increases heavy metals in cultivated lands (Rattan *et al*., 2002). Heavy metals decrease microbial biomass by directly killing or biochemically disabling organisms in soil. As a consequence, the amount of microbial biomass carbon (MBC) in agricultural soils supplied with sewage sludge or sewage sludge-containing composts was much lower than soil receiving FYM for the same period (Brookes and McGrath, 1984). Such information pertaining to other labile pools, particularly $KMnO_4$–oxidizable carbon, is virtually nonexistent.

Under incubation study at different moisture and temperature levels,Verma *et al*. (2011) observed that with the increase in extent of substitution of urea N, SOC measured by Walkley and Black method increased irrespective of the organic sources and consistently higher labile carbon ($KMnO_4$-oxidizable carbon) was maintained where 50 and 100% of urea N was substituted by organic sources. Increase in temperature had negative effects on soil organic carbon pools and by and large, lability of soil organic fraction was inversely related to moisture regimes.

Soil organic carbon fractions: an index of soil fertility

Soil organic fractions are well correlated with each other and act as a good index for soil fertility. Table 1 clearly explained that soil samples collected from different cropping systems showed good correlation among different fractions of soil organic carbon like WBC (SOC measured by Walkley and Black method), LBC or KMOC ($KMnO_4$ oxidizable carbon) and MBC (Microbial biomass carbon). It also revealed that availability of nitrogen, phosphorus and sulphur is also governed by these fractions because of having good correlations with the different fractions of soil organic carbon. The cycling of nutrients in soil of agricultural ecosystem depends on the varying degrees of energy supply to and through the soil biota. Labile source is the immediate sink of C, N, P, and S in soil and acts as a good indicator.

Haynes (2005) reported that the microbial biomass, while comprising a relatively small pool of N, P, and S, may cycle these nutrients perhaps eight to ten times per year.

Table 1 Simple correlation among different soil organic carbon fractions and available nutrients

Soil properties	WBC (%)	KMOC (mg g^{-1})	MBC (mg kg^{-1})
WBC (%)	1.00		
LBC(mg g^{-1})	0.82	1.00	
MBC (mg kg^{-1})	0.78	0.80	1.00
N (mg kg^{-1})	0.48	0.58	0.63
P (mg kg^{-1})	0.47	0.52	0.56
S (mg kg^{-1})	0.69	0.69	0.66

Total no. of sample = 88; all the values of *r* are significant at 1 % probability level

Source: Verma *et al*. (2010)

Carbon management Index

Changes in nutrient management practices within the agricultural system cause more subtle changes in the balance between inputs and losses of organic matter and thus in total SOM content, because of the relatively large quantity of background organic matter already present. Such changes are difficult to detect and are usually demonstrated in long-term (>25 years) experiments (Campbell *et al*., 1997; Christensen *et al*., 1997). Several studies attempted to identify labile pools of SOC which are more sensitive to changes in agricultural management practices and land uses than total organic carbon (Blair *et al*., 1995; Gregorich *et al*., 1997). Use of a single strength (333 mM) of $KMnO_4$ provided sufficient and reasonable characteristics of labile carbon to define the state of soil system. Estimation of labile pool of organic carbon provides information regarding the quality of organic carbon present in the soil as this fraction comprises readily oxidizable organic components including humic materials and polysaccharides (Blair *et al*., 1995; Blair, 2000; Graham *et al*., 2002), whereas, quantification of carbon in short term basis required another reliable parameter which can change significantly due to alteration of agricultural management practices and land uses. To estimate the carbon build up in soil in the short term basis, an index was developed by Blair *et al*. (1995) which is termed as Carbon Management Index (CMI). Carbon management index (CMI) was computed according to formula:

CMI = Carbon pool index (CPI) × Lability index (LI) × 100

Where, CPI = [Sample total C (mg g^{-1})/ Reference total C (mg g^{-1})],

Lability of C (L) = (Carbon fraction oxidized by $KMnO_4$/Carbon remaining unoxidized by $KMnO_4$), and

LI = (Lability of C in sample soil/ Lability of C in reference soil)

To measure the CMI, we need to know the total organic carbon content and carbon fraction oxidized by $KMnO_4$ in the sample soil as well as in the reference soil. For the reference soil, the value of CMI comes to 100. If there is gain of carbon in soil as compared to reference soil the value for CMI will increase. Changes of CMI provide the index of soil carbon buildup. Though there is no ideal value of CMI, the index provides a sensitive measure of the rate of changes in the soil carbon in the system related to the more stable reference soil (Blair *et al.,* 1995). Hence, Carbon management index (CMI) will be sensitive and useful for assessing and monitoring the dynamics of soil organic carbon under different agricultural management practices and land uses.

Conclusion

Soil organic matter is an extremely important attribute of soil quality, since it influences physical, chemical and biological properties and processes. Hence, the key to sustain productivity of agricultural system is the proper maintenance of soil organic matter level. Labile organic carbon fractions are more sensitive to the alteration in nutrient management practices compared to stabilized fraction of carbon in soil. For monitoring the impact of agricultural management practices on the quality (active fractions) of soil organic carbon, $KMnO_4$ oxidizable carbon proved to be a better index. Organic materials with wider C/N ratio (e.g., crop residues) had more impact on relatively stabilized fractions of SOC (quantity), while the same with narrower C/N ratio (e.g., Green manure) exerted more impact on the active fractions (quality) of SOC. Carbon management index (CMI) is proved to be sensitive and useful for assessing and monitoring the dynamics of soil organic carbon under different agricultural management practices and land uses.

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Greenhouse Gas Emissions from Livestock Manure

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Introduction

A greenhouse gas is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range (between 3.5 and 20 micrometers). This process is the fundamental cause of the greenhouse effect (IPCC, 2008). The primary greenhouse gases in the atmosphere are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). Livestock activities emit considerable amounts of CO_2, CH_4 and N_2O. Direct emission from livestock comes from respiratory process of animals in the form of CO_2. Ruminants to a major extent and monogastrics to some extent emit CH_4 either as eructation or flatus as part of their digestive process which involves microbial fermentation of feeds. Animal manures are also a substantial source of greenhouse gas emission in the form of CH_4, N_2O and CO_2 depending on the way they are produced (solid, liquid) and managed (collection, storage, spreading).

Global warming potential of greenhouse gases

Methane has a global warming potential of 25 times and N_2O 289 times that of CO_2 in a 100 year time horizon. Methane is one of naturally occurring organic compounds that has shown steep increase in concentration from historical levels. The key atmospheric oxidant of CH_4 is the hydroxyl radical, OH formed in the troposphere. However, reactions of CH_4 with O_2 or O_3 are very slow and relatively unimportant.

Majority of atmospheric N_2O is destroyed in the stratosphere by reaction with light and excited oxygen atoms. The breakup of N_2O molecules in this way takes place in an average atmospheric lifetime of around 114 years. It is this long lifetime that makes N_2O such a powerful greenhouse gas. The uptake of N_2O by soils is generally very small on a global scale. It is driven by de-nitrification by soil bacteria, which converts N_2O into nitrogen gas. Further, it has been shown that physical quality of the litter is more important than the microbial interference in this soil N_2O sink (Seneviratne and Somapala, 2003). Soil surface litter, mulches of leaves with a thick waxy cuticle that are hardly permeable to gas diffusion contribute to this physical mode of soil N_2O consumption, before their slow decomposition.

The restricted permeability to gas diffusion increases the residence time of N_2O produced in the soil, which allows to complete the conversion of N_2O to N_2.

Global contribution of CH_4 and N_2O emissions from agriculture

In 2005, agriculture contributed an estimated emission of 5.1 to 6.1 Gt CO_2 eq (10-12% of total global anthropogenic emission of greenhouse gases). CH_4 contributed 3.3 Gt CO_2 eq and N_2O 2.8 Gt CO_2 eq. of the global anthropogenic emissions in 2005, agriculture accounted for about 60% N_2O and 50% CH_4. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with net CO_2 emissions of only around 0.04 Gt CO_2 eq (Smith *et al*., 2007). Therefore, CH_4 and N_2O are the main greenhouse gases, to be taken care of from agricultural sectors. Emissions from soil and associated N inputs, such as synthetic fertilizer, animal manure and crop residues are the main agricultural N_2O sources. CH_4 emission as a share of total agricultural greenhouse gas emissions slightly declined (44% to 42%) over the 1990s, largely attributing to greenhouse gas emissions from livestock farming (OECD, 2008). Mosier *et al*. (1998) estimated that animal manure applied on soils contributed 0.3 Gt CO_2 eq yr^{-1}, which was equal to 10% of global N_2O emission. Another estimate indicated that direct emissions resulting from animal manure application is 0.2 Gt CO_2 eq yr^{-1} (IFA/FAO, 2001).

Manure management and emissions

Emissions to air and water bodies are to a certain extent unavoidable consequences of recycling of livestock manures within agriculture. Emissions arise from biological and chemical processes associated with degradation of organic materials during digestion of feed by animals and storage, treatment and land application of manures. Besides many methods of storage or treatment, stockpiling, dry storage, composting, liquid storage, gasification and pyrolysis are common.

Stockpiling of manure is just simply collecting the solid manure, livestock bedding, feed residue etc. and piling it up in a convenient location. This primitive method is generally practised in household or in farms having smaller number of animals. The spot is compacted and sealed so that rains falling on the pile cannot leach pollutants into the pool and underground water. It is crucial to have a vegetative filter strips to treat the runoff water coming from the manure pile. The nutrients uptake by grasses uptake, soil-filtering and adsorption and biological process in the top inches of soil significantly reduce pollution potential of manure runoff. The filter should be established in the form of a vigorous thick stand of grasses adapted to the soil condition at the site. On a flatter slope, the strip should be minimum of 30 feet wide.

Dry manures are stored at dry stack. It is suitable for small livestock operation. A dry stack facility has three walls to contain the manure. The best one has a concrete floor. It is usually covered to prevent the addition of extra water. The floor is slightly sloped for drainage out of the facility and the drainage runs to an adjacent vegetative filter strip.

Composting is the breakdown of relatively dry manure by microorganisms and fungi under aerobic, moist conditions. The most important factors influencing the rate and efficiency of composting are oxygen supply, temperature control and availability of water in the blend. Oxygen is required by the composting microorganisms to oxidise biodegradable materials. This makes turning and aeration of manure, an important factor for production of good quality compost. The higher the content of readily biodegradable material, the greater is the potential oxygen demands. If insufficient oxygen is supplied, anaerobic condition will result reducing quality, producing noxious and greenhouse gases. The structure and moisture content of a solid waste determines how easily it can be aerated, and on the type and quality of blending and bulking agents or carbon sources required (if any) to enhance porosity and absorb excess moisture. The mixture should have the moisture content of about 50 to 60%. The temperature of the compost is a good indicator of composting process/activity; temperatures within 40 to 60 ^{0}C promote maximum biological activity. Compost should have a pH within the range of 5.0 to 8.0. Insufficient N impairs the composting process, whereas excess nitrogen results in loss of N to the atmosphere by volatilization of NH_3, which may cause noxious odours. An ideal C:N ratio of 25-30:1 for raw waste is acceptable. However, nutrient status of compost is determined by the availability of C and N to microorganisms and therefore the required N content may differ between manures voided by grazing animals and animals fed with concentrate supplements. Composting is accomplished in two main stages – the active stage and the curing stage. In active stage, microorganisms consume oxygen while feeding on organic matter in manure and produce heat, CO_2 and water vapour. During this stage, most of the degradable organic matter is decomposed. In the curing phase, microbial activity slows down and the process nears completion, the material approaches ambient air temperature. The material would be reduced in volume by 20 to 60%, the moisture by 40% and weight by up to 50%. One of the key challenges in composting is to retain as much N as possible.

Liquid storage is used by large farms. The waste is diluted with stall wash water and pumped to a lagoon or other holding locations. From there the liquid effluent and the solids are pumped into an injector tank and spread in the field as a slurry. This type of storage and management system is usually more complex and expensive and is usually not practical for smaller livestock operation.

Research has often been focused on source level (e.g., CH_4 emissions from slurry storage) with the aim of establishing emission factors and assessing potential mitigation measures for that source. However, it is important that the whole-farm perspective is borne in mind, and that interactions such as secondary impacts on emissions from other sources and emissions of other pollutants are considered. For example some mitigation measures are aimed at reducing NH_3 emissions from livestock housing and manure storage, will result in potentially greater losses at manure spreading stage, reducing the overall effectiveness (Weiske *et al*., 2006), unless measures targeted at manure spreading are also imposed (Web and Misselbrook, 2004).

Gassification is a method for treatment of manure in which carbon compounds are converted into combustible gases under low oxygen condition and high temperatures leaving behind mineral ash. The gases contain CO, CO_2, CH_4, N_2 and H_2.

Pyrolysis is another method for treatment of manures. In this method, manure is converted into oil, char and waste gases under high temperature, pressure and absence of oxygen. The CO is pumped into the process to scavenge free oxygen and the C in the manure is transformed into burnable hydrocarbons similar to light crude oil. This method is a variant of the methods used to make charcoal from wood.

Production of CO_2, CH_4 and N_2O from manures

A large amount of organic matter in manure is actually partially digested feeds along with the bodies of bacteria from animal's gut. Carbon present in these in the form of proteins, fatty acids, lipids, carbohydrates, cellulose, lignins etc. are mineralized into CO_2 or converted to CH_4 during storage and treatment. The biological activities in the manure continues during storage and if the conditions are aerobic as exists in dry stack storage, poultry litter storage or system specially designed to aerate the manure, CO_2 will be given off and if anaerobic, CH_4 and smaller amounts CO_2 will be emitted. In aerobic condition, the N will largely remain in the manure as organic-N or ammonium. In anaerobic conditions a portion of N will be lost to the atmosphere as NH_3. The anaerobic lagoons are not just storage facilities. The pH of it remains to be at or above neutral compared to other storage facilities where it remains at acidic side. The N in anaerobic lagoon is converted to NH_4 and NH_3. Ammonification is accelerated by high pH and warmth and NH_3 is lost to the atmosphere. In aerobic lagoon, far less NH_3 is generated than in anaerobic condition; however, N is retained in solution as NO_3 and NH_4 and in the bodies of aerobic microorganisms as organic-N. The N converted to ammonium is mineralized to NO_3. Conversion of NH_4 to NO_3 might be slowed down due to lack of O_2 and intermediate NH_3 will be driven off.

When manure is stored in anaerobic lagoons, significant amounts of C are lost as CH_4. The anaerobic digestion is a multi-stage process. Communities of hydrolytic bacteria break complex organic matter to simple compounds. Acid forming bacteria convert the simple compounds to volatile fatty acids, principally to acetic acid. The other major compounds produced at this step are CO_2, H_2, NH_4 and S. The CO_2 helps in maintenance of anaerobic condition. Methanogens are CH_4 forming organisms that belong to Archaea domain. Methanogens take the end products of fermentation – volatile fatty acids, H_2, CO_2 and water and use them to form CH_4. Methanogens fall into two main groups depending on the pathways they use to produce CH_4. All methanogens that can reduce CO_2 and H_2 into CH_4 and H_2O are called hydrotrophic methanogens and methanogens that convert volatile fatty acids and number of other simple organic compounds to CH_4 and CO_2 are called acetotrophic methanogens. Methanogens thrive in two temperature ranges. Thermophillic (heat loving) methanogens are fast growing with a reproduction time of 10 to 15 days, but they operate in a fairly narrow band of temperature centred on 55°C. Mesophillic methanogens are slow growing with a reproduction time of up to 30 days but they tolerate wider range of temperatures. The optimum temperature for mesophillic methanigens is 35°C but they can also tolerate much lower temperatures. The gases given off during anaerobic digestion contain 40 – 70% CH_4. The presence and population of methanogenic bacteria are important for CH_4 production. Manure from ruminants contains more methanoganic bacteria than manure from non-ruminant animals. Temperature affects the rate of biochemical reactions, the types of functioning of microorganisms and therefore the rate of CH_4 production. The greater the energy content and biodegradability of the feed, the greater is the CH_4 production potential of the manure. For example, manure from animals fed with grain based, high energy diets are more degradable and has higher CH_4 production potential than manure from animals fed with roughage diet. Every manure has a maximum (ultimate) CH_4 production potential which is determined by its chemical composition. The maximum CH_4 production potential is defined as the quantity of CH_4 that can be produced per unit mass of organic matter, with unit cubic meters of CH_4 per kg of organic matter. The effect of animal diet on maximum CH_4 production potential is presented in Table 1.

Table 1 Methane production potential of animal manure as affected by different diets

Animal type	Diet	Methane yield (m^3 kg^{-1} organic matter)[a]
Swine	Maize-based, high energy diet	0.44-0.52
	Basely based diet	0.36
Dairy cattle	58-68% silage	0.24
	72% roughage	0.17
Beef cattle	Maize-based, high-energy diet, manure collected from concrete	0.33
	7% Maize silage, 87% maize, manure collected from dirt lot	0.29
	91.5% Maize silage, 0% corn, manure collected from dirt lot	0.17
Poultry	Grain-based diet	0.39

[a]Volume of methane under standard conditions of 1 atmosphere of pressure and 25^o C

Animal manure typically contains sufficient nutrients to support microbial growth. Moisture content relates to availability of water to the microorganisms and the ability to maintain an oxygen free environment in the manure. More than 80% moisture content is conducive to CH_4 production. Manure as excreted contains 70-91% moisture. It's moisture content may change to higher or lower amounts depending on the method of manure collection, handling and storage used in the animal waste management systems. Based on the total solid contents of manure and the requirements for different handling and storage methods used, the management systems can be categorized into 3 types: (1) solid system (Total Solid > 20%), slurry system (TS = 10 – 20%) and (3) liquid system (TS < 10%) (MWPS, 1985).

Examples of solid system are solid manure storage, dry lot, deep pit stacking and litter; slurry system - under-floor deep pit storage and slurry storage and liquid system - anaerobic lagoon.

CH_4 production potential increases in the order: solid manure, slurry manure and liquid manure systems based on chemical environment present such as oxygen, moisture and inhibitory substances. In manure, both thermophillic as well as mesophillic methanogenic bacteria, especially the *Methanosarcina thermophila*, *Methanosarcina mazei*, *Methanothrix thermoacetophila* and *Methanobacterium thermoformicicum* are responsible for CH_4 production. In fermenting manure, acid-utilizing methanogenic bacteria play the leading role in contrast to rumen microbes (Nozhevrcikova *et al.*, 1988). Methanogenic bacteria are obligatory anaerobes. They are also sensitive to low pH of the manure. The optimum pH for CH_4 production is near 7.0 but CH_4 can be produced in a pH range from 6.2 to 8.5 and a pH beyond this range CH_4 production will decrease. The retention time of the manure in the storage systems is also an important factor. If all other conditions are the same, longer times will lead to more CH_4 production. However, presences of inhibitory substances like antibiotics, sulphate, sulphide, salt and NH_3 at higher levels also affect CH_4 production (Table 2).

Table 2 Effect of ammonia and sulphide concentration on anaerobic digestion of manures

Effect on anaerobic digestion	$NH_4^+NH_3^-$ N (mg/l)	S^- (mg/l)
Beneficial	50 - 200	< 50
No adverse effect	200 - 1000	50 – 100
Inhibitory at higher pH values	1500 - 3000	100 – 200
Toxic	> 3000	> 200

Composting is one of the most prevalent methods practised in the developing countries. In this method, the carbon-containing compounds are attacked by bacteria, actinomycetes and fungi under aerobic conditions and carbon is mineralized to CO_2. Some CH_4 is produced in the interior particles where there is little oxygen. Therefore, so much of C is consumed for which the mass may shrink by 50% or more.

Manures are sometimes applied directly in the field or the animals defecate directly in the field during grazing. In this condition, the transformation of carbon containing compound is similar to the composting process but takes place more slowly and without the increase in temperature. Organisms in the soil mineralize carbon in manure into CO_2 which is given off into the atmosphere or retained in the soil gases. Some of the carbon is bound in the soil as humic acid (soil organic matter). If the ratio of carbon to nitrogen is high, for example, if the manure contains a lot of straw, sawdust etc. or there is a large amount of residue on the soil surface, the available nitrogen in the soil may be immobilized by bacteria decomposing the carbonaceous material, leaving plants with less nitrogen than they need for successful crop production. High carbon manures, including poultry litter, cattle manure benefit from composting.

The microbial process of nitrification and de-nitrification are the predominant sources of N_2O production from manure. Nitrification is the oxidation of NH_4 to NO_2^- or NO_3^- by heterotrophic and autotrophic nitrifying bacteria. During this process, N_2O can be formed by the oxidation of hydroxylamine, an intermediate or reduction of nitrite (Firestone and Davison, 1989; Bender and Conred, 1994).

Denitrification is the anaerobic reduction of NO_3^- to N_2 during which N_2O is formed as an intermediate product and can diffuse from the manure (Firestone and Davison, 1989). Anthropogenic sources are largely responsible for the increasing concentration of N_2O in the atmosphere. Direct emissions from agricultural soil are estimated to be above 25% of total anthropogenic sources of N_2O to the atmosphere.

Fertilized soils are important source of N_2O. The global direct N_2O emission from fertilized agricultural soil are estimated at 0.9 Tg N year $^{-1}$ for soils fertilized with mineral N fertilizers and 0.6 Tg N year^{-1} for soil fertilized with animal wastes (Mosier *et al*., 1998).

Fertilizer and manure types may affect N_2O emission in several ways i.e. (i) the type of N (NO_3^- , NH_4^+ and organic N) which affects N_2O production during nitrification and denitrification activities, (2) the presence of easily available carbon which stimulates denitrification activity and O_2 consumption of the soil following its application and (3) effects on biological, chemical and physical soil processes because of change in pH and the addition of other components (salt, water). Animal manures are mixture of mineral N, easily mineralizable and resistant organic N and C compounds, salts and water. There are large differences in composition between animal manures, due to animal species and nutrition (Chadwick *et al*., 2000). In general, the degradability of organic C and N of cattle manure is smaller than that of pig and poultry manure. It is expected that animal manures with a relatively high content of mineralizable C result in higher N_2O emissions after soil application than animal manures with more resistant C. In current IPCC methodology the amount of N applied is considered as a major factor controlling N_2O emission from agricultural soils (Mosier *et al*., 1998). One single N_2O emission factor of 1.25% of total N applied is used for all types of fertilizers and manures and application techniques. This suggests a linear relationship between the nitrogen applied and N_2O emission. In daily agricultural practices, many different animal species are kept. These species have distinct feeding rations and are housed in specific stables. Many different manure storage and processing practices are in use and manure application techniques also vary widely. The N_2O emission from pig manure placed in a row at 5 cm depth was reported to be higher than from surface application. High emissions are associated with manures with high content of inorganic N, easily mineralized C, such as liquid pig manure compared to cattle and poultry manure (Velthop *et al*., 2003).

Strategy to reduce greenhouse gases emission from manure

Feeding of livestock influences nutrient flows and pollution sources at farm level in many different ways. Nutrient found in manure originate from the fraction of feed which is not retained by the animals. It indicates that manipulation of diet could be an effective way to control the amount of the manure produced and its composition.

For monogastric animals, especially in pigs and poultry, significant advances have been made using this approach. However, in ruminants, with added complication in digestion of forage based diets in the rumen, a significant potential has been identified (Clemens and Ahlgrim, 2001).

Dietary measure

Improving feed N and energy utilization through dietary measures without negatively affecting animal productivity is considered a possible way to reduce greenhouse gas emissions through decreased N and energy contents in urine and faeces (Oenema *et al*., 2001). N excretion from animals might be reduced by improving the match between protein quality required and provided to the animals in their diets and increasing productivity so that animal based human food products can be produced with less consumption and excretion of nitrogen. Pomar (1998) indicated that about 50% of total N excretion by pig could be reduced by modifying the composition of the diet without any impairment of performance by balancing amino acid composition of diets and phase feeding. It would reduce the mass of N_2O emission/ unit animal product (Rotz, 2004). For growing-finishing pigs, a 0.1% decrease in feed to gain ratio there is a 3% decrease in N excretion (Henrey and Dourmad, 1992). Types of fodders offered to the animals also affect the N_2O emission from the manure. Feeding ensiled ryegrass (*Lolium bybridicum*) to sheep resulted in lower N_2O emission from manure than lucern (*Medicago sativa*) and kale (*Brassica oleracea*). It might be due to larger soluble organic C content of the ryegrass slurry which produced the lowest N_2O/N_2 ratio compared to other treatments (Cardenas *et al*., 2007). However, reduced N excretion through diet manipulation could reduce the overall N surplus on farms, resulting in lower rate of manure application and reduced N_2O emission from manure N.

Management of manures

Management of manure is very important as more than 90% of greenhouse gas emission in the form of CH_4 is observed within 80 days of retention (Amon *et al*., 2006). Greenhouse gas abatement measures are most effective if they reduce CH_4 emission during storage. Treatment involving altering manure characteristics by separation of solids, composting, aeration and anaerobic digestion are effective in reducing greenhouse gas emission compared to untreated manure.

Altering manure characteristics by separation: In solid-liquid separation method, manure is divided into solid and liquid fractions. Additional separation of liquid fraction into supernatant and sediment fractions can be achieved by adding a flocculent (e.g., polyacrylamide) that removes suspended particles. Separation has agronomic benefits, such as ability to use the supernatant for fertigation (VanderZaag *et al*., 2011).

Total greenhouse gas emission from untreated, separated, digested, straw covered and aerated dairy slurry was observed to be 92.4, 58.5, 37.9, 120.0 and 53.3 kg CO_2 eq m^{-3}, respectively during storage, solid stockpile and reuse (Amon *et al*., 2006). Similarly, increases in greenhouse gas emissions following the application of straw covers to slurry storage was reported by Berg *et al*. (2006) and Cicek *et al*. (2004). Possible reasons for the increases include sinking straw providing additional C source for methnogens and reduced surface mixing maintained optimum anaerobic conditions both of which resulted in increased CH_4 emissions. In addition, straw in the surface between the atmosphere and N containing slurry provides an environment for uncontrolled nitrification and de-nitrification resulting in N_2O emission. However, conflicting results have also been reported by Sommer *et al*. (2000) and Lague *et al*. (2004).

Composting: Composting of solids separated from the effluent stream offers some potency in the overall reduction of greenhouse gas emission. Separated solids must undergo true aerobic composting to mitigate greenhouse gases. Though stockpiling or minimal intervention composting of solids without turning is simple and effective means of reducing volume and volatile solids it should not be termed as true composting as aerobic condition is not maintained uniformly. Due to presence of anaerobic condition in some pockets, CH_4 production still continues.

However, forced aeration and turned windrows are observed to be effective measures during composting procedures and substantially reduce CH_4 emission compared to static stockpiles (Lopez-Real and Baptista, 1996).

Therefore, if the separated solids are not composted with due to high C:N, low porosity and moisture content, CH_4 emission would remain high and additional N_2O emissions might be produced as a result of incomplete de-nitrification and nitrification under unfavorable conditions and it has been demonstrated that 25% higher greenhouse gas was produced from liquid and separated stockpile solids than untreated control pig manure (Dinuccio *et al*., 2008).

The N_2O emissions after liquid manure application were nearly 3 folds more compared to that with solid manure and a much larger N fraction was lost as N_2O from liquid manure (Gregorich *et al*., 2005). This might be due to the fact that liquid manure added labile carbon and moisture, lowering O_2 availability. On the other hand solid manure often has higher total N, but it is mineralized slowly (ideally becoming available when the plants need it) so that less is available in the short term for de-nitrification. Thus, it is possible that short term studies don't adequately capture N_2O losses from solid manure that would occur over years (Ginting *et al*., 2003). Higher N_2O emission may result from direct slurry application in the field compared to solid manure, based on same nitrogen application rate. However, this will be offset to some extent as higher N losses from solid manure and bedding are observed during storage of solid manure prior to field application. In contrast, there is little N_2O emission from slurry based systems until land spreading. Thus, the apparent difference in N_2O flux between solid and liquid manure might not be representative of the reality (VanderZaag *et al*., 2011).

Anaerobic digestion: Anaerobic digestion of manures increases CH_4 production. The gases produced in the anaerobic digestion system, termed as biogas, is composed of 60-70 % CH_4, 30-40 % CO_2 and trace amount of other gases (H_2S, NH_3, H_2, N_2, CO). Biogas may be used as a fuel if it contains at least 50% CH_4 in its composition. Biogas must be cleaned in terms of its H_2S content, if it is used in mobile engines. Removing any moisture and CO_2 upgrades the biogas and increases its fuel value.

Biogas can simply be burnt so that instead of CH_4, the combustion products CO_2 and H_2O are discharged. Burning of one molecule of CH_4 yields only one molecule of CO_2 reducing the global warming potential by a factor of 21 times. It can be used for production of hot water using in boiler, generation of electricity and milk cooling by using it in absorption chillers, which are heat driven. It can be aimed at reducing greenhouse gas in terms of carbon credit. Besides the above uses, it is passed through bio-filters where some of the CH_4 is oxidized by aerobic bacteria. However, the bio-filters may not be a good option as it shows variable performances and difficulties in measuring reduction.

The digested manure (digestate) has a number of unique characteristics including a higher pH, which could promote NH_3 losses, lower dry matter (DM) content and viscosity, which could reduce NH_3 losses by infiltrating in to soil more rapidly (Amon *et al*., 2006). However, emission of CH_4 and N_2O were higher from digestate (397 g CO_2-e kg^{-1} DM) than form composted dairy manure (static pile filled with two air supply pipes; mostly aerobic; 207g CO_2-e kg^{-1} DM) over a 90-day storage period. Emission from stockpiled dairy manure solids (partially anaerobic, partially aerobic) fell between the other two treatments at 301 g CO_2-e kg^{-1} DM) (Pattey *et al*., 2005).

Further, the digestate may contain relatively more NH_4-N and less organic carbon resulting in a lower C:N, all of which are properties that tend to increase the ratio of N_2O:N_2 produced by de-nitrification (Wulf *et al*., 2002; Amon *et al*., 2006). Digestate also contains less metabolizable organic C, which limits the available C for soil microorganisms and decreases N_2O emissions. It is proposed that anaerobic digestion could reduce direct N_2O emissions from liquid manure applied to soils by 20-40% (Peterson, 1999). These N_2O reductions are consistent with the results of Clemenns and Huschka (2001), who conducted a laboratory study using undigested and digested cattle slurry. During the first 8 days application, N_2O emissions were dominated by de-nitrification, a result attributed to the level of easily available organic substances in the digestate measured as biological oxygen demand (BOD). N_2O emissions were positively correlated with BOD and soil moisture. Overall, N_2O emissions were reduced by anaerobic digestion at low (35%) and medium (54%) water filled pore space (WFPS) but there was no difference at high WFPS (71%). Overall, there is consistent evidence that anaerobic digestion reduced NH_3 losses upto 45%, and N_2O emission up to 70% on moderately well drained soils. These emission reductions, combined with economic benefits of anaerobic digestion make it attractive mitigation strategy. However, N_2O emissions were measured for a few weeks in most studies and long term measurements are needed. Another aspect that needs further studies is addition of off-farm materials that increase biogas yield (e.g., co-digestion with food waste). These feed stocks direct more N to agricultural lands, often with a high proportion of ammonium-N, thereby increasing the risk of direct and indirect N emission.

Manure application

Method: There are numerous methods of applying manure in the field that depend on manure characteristics, cropping systems, soil types and farm management constraints. Solid manure is typically applied to soil surface and is subsequently incorporated. Liquid manure application methods can be grouped into the categories of surface spreading, surface spreading along with incorporation where the manure is applied to the soil surface and tilled into the upper layer of soil, shallow injection and deep injection to a depth > 10 cm.

Deep injection of slurry was observed to be the best application method on arable land, reducing NH_3 loss by 90% compared to surface application on bare soil. For grasslands, shallow injection was the best option as it reduced NH_3 losses by 70% (Rotz, 2004). These finding are supported by other workers where shallow injection reduced NH_3 loss by 73% when cattle or pig slurry was applied to grassland (Misselbrook *et al*., 2002). However, optimal application method also depends on soil condition. In tilled crop land, injection tends to decrease N_2O loss in dry soil but increases it in moist soils because slurry is concentrated at the injection sites causing anaerobic condition that facilitates N_2O production (Flessa and Beese, 2000). To reduce total direct and indirect emissions, it is better to apply manure to the surface of the arable land and immediately incorporate it with a harrow. Similarly, it was better to apply manure to the surface than to use deep injection.

Rate: Manure application rate determines the amount of C and N added to the soil. For liquid manures, rate also affects O_2 diffusion and high application rates can lead to surface sealing and anaerobic condition in soil (Stevens and Cornforth, 1974). Velthof *et al*. (2003) found a linear relationship between N application rate of liquid pig manure and total N_2O flux over ~ 100 days, whereas, Jarecki *et al*. (2009) reported a non-linear response wherein N with the increase in application rate a larger fraction of N was lost as N_2O. Other researchers have proposed that rate of N application is not the most relevant predictor of N_2O emissions, but that it is field level N surplus which is more important as it has been linearly co-related with N_2O fluxes from pasture and maize fields (van Groenigen *et al*., 2008). Other forms of N loss are also affected by application rate.

Tillage: Zero or minimum tillage systems which reduced the frequency of tillage, potentially leave the soil more moist and compact thereby impending oxygen transfer to microbes and promoting N_2O production. One study over two seasons with two fields found no till plots receiving surface applied semisolid cattle manure had nearly two fold higher N_2O fluxes than conventionally tilled plots receiving the same manure (Mkhabela *et al*., 2008).

Timing: With inorganic fertilizer, there is experimental and modeling evidence that N_2O fluxes can be reduced by applying fertilizer in the spring rather than autumn. This is partly because spring application avoids potentially high N_2O emissions during periods of high moisture in late autumn and early spring (Gregorich *et al*., 2005). As a result, higher emission factor has been used for N_2O emissions for fertilizer and manure applied in the autumn as compared to spring in Canada (Helgason *et al*., 2005); emission factors that assume N_2O emissions from the manure N are the same as from inorganic fertilizer N. However, there is little published data on manure timing to verify this. Timing of manure application also affects NH_3 emissions, which increases as a function of temperature and wind speed. On seasonal basis, less volatilization can be expected in cooler months, which suggests that autumn and spring application would result in lower emissions than summer. However, it is also reported that a 50% reduction of NO_3 leaching loss could be achieved by moving autumn manure application on arable land to spring (Seppard and Chambers, 2007). So, shifting manure application to spring from autumn reduces NO_3 leaching upto 50% and avoids higher N_2O fluxes during spring thaw. The overall impact on N_2O emissions however is complex and without research it cannot be generalized as a simple seasonal effect.

Improving feed efficiency

Improved feed efficiency will be helpful to minimize total dry matter requirement in the farm that would subsequently reduce total volume of manures voided by the animals. Using balanced feed with the highest digestibility might be an option for reduction of greenhouse gas emission. Lesser is the amount of volatile solids and N to be decomposed the less will be the emission of CH_4 and N_2O.

Properly managed composting

Maintaining recommended process parameter is much essential for proper composting with minimum level of greenhouse gases. Stockpiling of manures without turning is not composting. It is indicated that composting manure results in reduced greenhouse gas emission, particularly for CH_4 emission. Stockpiling resulted in 1.46 times more greenhouse gas emissions than composting (Pattey *et al*., 2005).

Separation of solids

Solid-liquid separation of animal waste before anaerobic fermentation of slurry and composting of solids would be a good option in reducing overall greenhouse gas emission.

Retention of crusts on anaerobic ponds/lagoons

Retention of crusts on the surface of ponds/lagoons where biogas capture is not an option, provide an environment for bacterial oxidation of CH_4.

Direct application or minimizing retention time

The direct application of manure in the field helps to avoid anaerobic storage and production of CH_4. However, possible pollution of surface and ground water and likelihood of increased emissions of N_2O creates more risks than it resolves. However, reducing retention time of effluents helps in reduction of CH_4 production.

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Perspective of Food Security through Inland Fisheries and Aquaculture in Climate Change Scenario

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Introduction

The major environmental challenge of 21st century is global warming and the associated climatic changes. Climate change is projected to impact broadly across ecosystems, societies and economies, increasing pressure on all livelihoods and food supplies, including those in the fisheries and aquaculture sector. Since fisheries and aquaculture depend heavily on climate, it is imperative to think of the vulnerability and adaptation strategies in dealing with the impending change. Fishery sector is expanding day by day and its share in the agricultural GDP is increasing every year.

Fisheries and aquaculture sector in India provides nutritious food, has high potential for rural development, domestic nutritional security, employment generation, gender mainstreaming as well as export earnings. India is a major maritime state and an important aquaculture country in the world with third position in fisheries and second in aquaculture and is now considered as a sunrise sector.

Table 1 Annual fish production in India

Fish Production	1950-1951(Mt)	2004-2005 (Mt)	2007-2008 (Mt)
Marine fish	0.53	2.78	2.97
Inland fish	0.218	3.52	4.19
Total	0.75	6.3	7.16

(Source: Hand book of Fish Statistics, MOA, GOI, 2008)

Its contribution to national GDP is 1.07 %; contribution to national agriculture and allied activities is 5.84 %; Indian share in global fish production is 4.36% with 9.92 % in inland and 2.28% in marine fisheries; direct and indirect engagement in fisheries sector is 14 million people; it has high export potential and presently 50 products are being exported that contributes 18% to the country's agricultural export. There has been significant increase in fish production in the country (Table 1) over the past six decades (Anonymous, 2008)

Impact of climate change on inland fisheries

While many of the changes impede development of fisheries and aquaculture, but few also provide opportunities for adaptation (Table 2)

Table 2 Likely influence of climate change on inland fishery

Change		Effects
Enhanced water temperature	Culture system	• Reduced water quality (DO) • Enhanced primary productivity • Increased growth and food conversion • Increased disease incidence • Enhanced breeding period in hatcheries
	Operational	• Changes in level of production (ponds, hatcheries) • Increase in capital costs (aeration, deeper ponds)
	Rivers	• Geographic shift of fishes, species richness • Breeding failure • Habitat loss/gain
	Wetlands	• Increased stratification and reduced mixing of water in lakes and reservoirs • Reduction in primary productivity and food supply to fish species
Floods due to changes in precipitation	Culture system	• Salinity changes • Structural damage • Escape of fish stock • Introduction of disease and predators
	Operational	• Loss of fish stock • Damage to facilities • Higher capital costs for flood resistance • Higher insurance costs
	Rivers	• Changes in fish migrations and requirement patterns
Intense storm surges (coastal region)	Culture	• Inundation and flooding • Salinity changes • Escape of fish/prawn stock • Introduction of disease and predators
	Operational	• Loss of prawn/fish stock • Damage to facilities • Higher insurance costs
Drought (as an extreme event, as opposed to gradual reduction in water availability)	Culture system	• Salinity change • Reduced water quality • Limited water volume for aquaculture • Increased competition with other water users
	Operational	• Loss of fish stock • Limited production
Sea level rise		• Loss of land • Changes to estuary system • Loss of coastal ecosystems such as mangrove forests

Contd.....

Water stress (as a gradual reduction in water availability (trend) due to increasing evaporation rates and decreasing rainfall)	Culture	• Decrease in water quality • Increased diseases • Reduced pond level • Altered and reduced freshwater supply
	Operational	• Additional cost for maintaining pond level artificially • Conflict with other water users • Loss of fish stock • Reduced production capacity • Change of culture species
Human adaptation to changes in climate	Aquatic ecosystems including Fish and Fisheries Exacerbation of negative impact	
Example 1 : Increased demand of water for irrigation		
	Supply side options	Increasing supply, expensive, environmental impact
	Demand side options	• Reducing demand • Increase irrigation efficiency • Higher prices • Changes in cropping pattern
Example 2 : Flood management control flood		
	Supply side options	• Increasing flood protection with levis, and reservoirs • Expensive • Environmental impact • Catchment source
	Demand side options	• Improvement in flood warning system and information

Source: Das and Sharma, 2010

How would inland fisheries cope with climate change?

Enhanced temperature

Growth of Fish -Temperature changes will have an impact on the suitability of species for a given location. In temperate areas increasing temperatures could bring the advantages of faster growth rates and longer growing seasons. Similarly, for the Indian major carps in the tropical country like India, upto 33ºC the growth rate increases but from 34ºC and above feeding is reduced and growth diminishes.

Investigations were conducted to assess the impact on the growth of Indian major carp, *Labeo rohita*, fingerlings reared at elevated temperature in seven thermostatic aquarium for five weeks at water temperature of 29ºC, 30ºC, 31ºC, 32ºC, 33ºC, 34ºC and 35ºC. Fish reared at 34ºC water temperature exhibited a significantly ($P<0.05$) faster (SGR-2.36 % body weight per day) than those at other temperatures. The change in growth rates were insignificant between 29ºC, 30ºC, 31ºC and 32ºC treatment groups but growth rates significantly increased in the temperatures ranging from 32ºC to 34ºC and there after it decreased. A linear growth model of *Labeo rohita* fingerlings growth has been developed which provides a reliable projection of growth (SGR %) with unit rise of temperature within the range of 29º to 34ºC. Assuming these growth rates constant, it would take average 77 days for a fish to double its weight at 30ºC to 33ºC and 35ºC, but at 34 ºC it would take only 35-36 days (Das *et al*., 2011).

Enhanced breeding period of fish -Inland aquaculture is centered around the Indian major carps, *C. catla, L. rohita and C. mrigala*. These fishes are bred in captivity by the technique of hypophysation and their spawning occurs during the monsoon season (June-July) and extends till September. In recent years, the phenomenon of IMC maturing and spawning as early as March is observed (Dey *et al*., 2007).

Elevated temperature (by 0.37ºC – 0.67ºC) and alteration in the pattern of monsoon proved a major factor for shifting the breeding period of Indian major carps from June to March in fish hatcheries of West Bengal and Odisha. Investigations conducted indicate an extended breeding period of Indian major carps by 40-60 days, with breeding season extending from 110-120 days (Pre1980-85) to 160-165 days (2000-2009) at present in fifty fish seed hatcheries in four districts of West Bengal, India *viz*., North 24 Parganas, Bankura, Burdwan and Hooghly. This has provided opportunities to the farmers to avail of the extended breeding period in producing valuable fish seed and supplement their income (Dey *et al*., 2007).

Geographical shift of fishes -A perceptible shift was observed in geographic distribution of the warm water fish species, *Glossogobius giuris*, *Puntius ticto*, *Xenentodon cancila* and *Mystus vittatus* towards the colder stretch of the river Ganga up to Haridwar with an enhancement of annual mean minimum water temperature of 1.5ºC in the Haridwar stretch during the period 1970-86 to 1987-2009. This stretch has become a congenial habitat for these warm water fishes of the middle stretch of the river. As a result, fishers would have an enhanced yield and diversity in their fish catch from the stretch (Vass *et al*., 2009).

Adaptation options

- These options can primarily be affected in the culture system
- Making changes in feed formulations and feeding regimes of fishes
- Exploring substitution by alternate species of fish
- Providing monetary input to the changes in operational costs in ponds and hatcheries

Flood

Increased flooding may expand the number and quality of water areas available for cultivating fish. The unprecedented floods in Bihar during 2008 caused huge loss to life, property, agriculture and fisheries but at the same time the post flood management measures provided opportunities to fisheries and aquaculture in offsetting some of the losses incurred by the people.

Adaptation options

Post- flood

- The floods affected 6051 ha of fish culture areas in various districts of Bihar.
- The post flood fish seed requirement for stocking this area at the rate of 50 kg ha^{-1} of 5-10 g size of fish was 300 t.
- Thus continuous supply of fish seed from hatcheries or raising of fish seed in hatcheries is required.
- Cage culture in large waterlogged bodies for raising seed from fry to fingerlings.

Pre- flood

- Harvesting fish at smaller size.
- Giving importance to fish species that require short culture period and minimum expense in terms of input.
- Increasing infrastructure, sophistication of hatcheries for assured seed production of 34,000 million carp fry, 8,000 and 10,000 million scampi and shrimp PL, respectively.

Intense storm surges and sea level rise

Increased flooding may expand the number and quality of water areas available for cultivating fish. This will have wider applicability as coastal- floodplain zones expand with rising sea level and storm surges. During the cyclone Aila devastation in West Bengal, more than 70% people were either made homeless or had their livelihoods disrupted. Damages included loss of income, destruction to fish ponds, bheries and gear, and other assets. Fishers were totally dependent on fishing and collecting wild fish seeds from natural resources as the only source of income (Das and Sharma, 2010).

Adaptation options

Post ingress

The ingressed saline water inundated paddy fields which became unfit for agriculture. These areas provided temporary opportunities for converting these areas into ponds for fish culture with saline tolerant fish species *viz.*, *Mugil parsia, M. tade and Lates calcarifer.*

Pre-ingress

- Early detections systems of extreme weather events.
- Communication of early warning system.
- Accept certain degree of loss.
- Development and implementation of alternative strategies to overcome these periods.
- Maximizing production and profits during successful harvest.
- Suitable site selection and risk assessment work through GIS modeling.
- Increasing infrastructure, sophistication of hatcheries for assured seed production.

Drought

During the 2009 drought in West Bengal, the deficit in rainfall was within the range of 25% and 37% during the fish breeding months (April to Sept) in districts of Bankura and N 24 Paragana, respectively compared to the previous years. This has created a situation of water scarcity in fish rearing and culture pond of West Bengal. Breeding commenced in the month of March but the total number of successful days were restricted to 98 during 2009 in comparison to 150-155 days in the previous years. The total fish spawn production came down to 40 lakhs per 100 kg fish brooders from 130-140 lakhs per 100 kg in fish seed hatcheries in Bankura (Das e*t al*., 2011).

Adaptation options

Pre- drought

Eighty percent (80 %) of the hatcheries due to the drought condition diverted from rearing Indian Major Carps to other species like Pangasius (*Pangasius sutchi)*, *Puntius javanicus* and *C. garipenus*, which favourably adapt to water stress and high temperature condition.

Post- drought

Smaller ponds that retain water for 2-4 months can be used for fish production with appropriate species (catfish, tilapia etc.) and management practices.

Water stress (as a gradual reduction in water availability due to increasing evaporation rates and decreasing rainfall)

Prediction for water availability as a result of climate change in India indicate water stress in the coming years. This would result in decreasing water availability in the major river basins of India. The Gangetic plains and delta are regions of significant aquaculture activity contributing to income and providing livelihood to thousands of fishers. Thus, judicious use of this primary resource is of topical importance for sustaining fisheries and aquaculture in reservoirs, wetlands and other ponds and tanks.

Pond aquaculture for culturing shrimp and carnivorous fin fish species is water consuming but other technologies such as cage culture is totally non-water consuming, except for the need for feeds.

Adaptation options

- Multiple use, reuse and integration of aquaculture with other farming systems.
- Intensification of aquaculture practices in resources of waste water and degraded water such as ground saline water.
- Smaller ponds (100-200 m^2) of seasonal nature (1-4 months) can be used for rearing /culture of appropriate species of fish/prawn.

Carbon management in inland fisheries

Many studies on energy consumption associated with aquaculture and its significance with carbon emissions; associated with embodied energy use in inputs; emissions from land conversion and from soil, water and waste management have been undertaken. A review of these studies indicate some of the facts mentioned below.

Carbon sources and aquaculture systems

Direct energy consumption in intensively managed aquatic farming systems, especially for shrimp and salmon, has been assessed. However, the majority of global aquaculture production is of freshwater fin fish from semi-intensively managed ponds in Asia, but audits of the associated direct and indirect energy use are not routine. Indirect or embodied energy consumption is associated with site development and construction; production, acquisition and supply of inputs; waste handling and disposal; product processing, marketing and distribution.

Soil, water and waste management

Sediment management in pond-based aquaculture systems can have a significant effect on the accumulation of carbon and release of greenhouse gases. Sediments tend to accumulate in the deeper parts of ponds, reducing the water volume available for cultivation and through various processes negatively impacting water quality. Commonly, to avoid such problems, ponds are periodically drained and accumulated sediments is exposed to the atmosphere to promote organic matter mineralization. Tilling is also sometimes employed to promote more rapid oxidation, and lime is routinely applied to increase pH and disinfect the pond; liming also neutralises acidity and increases total alkalinity and hardness (Xinglong and Boyd, 2006). Exposure of pond sediments can result in loss of soil carbon through microbial processes as carbon dioxide; however, failure to manage sediments can result in the evolution of more damaging greenhouse gases, notably methane.

Biomass crops for onsite substitution

Biomass crops cultivated onsite and used to substitute for direct fossil fuel and electricity use offer a potential cost saving and strategy to reduce net carbon emissions. Furthermore, using unexploited waste resources, nutrient rich water or sediments, to enhance production could contribute further to environmental protection. Several approaches to treating aquaculture wastewater with constructed wetlands planted with various macrophytes (reeds, mangrove fern, mangrove trees, halophytes) have been found beneficial.

Enhanced soil, water and waste management

Carbon stocks and flows can be significant in semi-intensive and intensive aquaculture systems, where primary production is enhanced with organic and inorganic fertiliser or supplementary feed. Therefore, management strategies are required to optimise the assimilation or long-term storage of carbon in such systems. The organic carbon content of sediments in pond-based aquaculture systems seldom exceeds 5% (Boyd, 1995). Enhanced pond bottom management strategies should focus on protecting excessive accumulation and mineralization of soil organic carbon and promote *in situ* assimilation of soil organic carbon. Where sediment removal is practiced, it may be ensured that this material is properly managed and applied elsewhere to improve soil quality and enhance soil carbon stock.

Enhancing aquaculture associated carbon sequestration

Opportunities to harness productivity and other ecosystem services in aquatic systems to sequester carbon are

Biomanipulation: Aquaculture India and in other Asian countries is predominantly dependent on fish species feeding low in the food chain and act as carbon sink and aid in carbon sequestration though cultured shrimp and carnivorous finfish which feed mainly on fishmeal and fish oil.

Aquaculture of Indian and exotic carp uses minimal industrial energy but has significance in the carbon cycle, fixing CO_2 through phytoplankton. Aquaculture thus has the scope of alternative practices being adopted in response to climate change and reduce the sectors contribution to GHG emission (Das and Sharma, 2010).

Adoption of simple techniques of providing a suitable and/or enhanced food source(s) for cultured stock through measures to increase phytoplankton and periphyton growth could be a major energy saving measure.

Periphyton-based practices have developed independently and are used to catch fish in open waters in various parts of the world. In West Bengal, the practice is known as *Komor* or *Huri*: in Bangladesh it is called *Katha*, in West Africa *Acadja* and in Cambodia *Samarahand*. In West Bengal, the practice is essentially fixing vertically unused bamboo sticks, tree branches to act as substrates for colonization by the plankton, microbes, invertebrates and other organisms that make up periphyton. The farmers in this part of India and Bangladesh traditionally believe that shaola (periphyton) growing on the substrate form food for the fish and serve as protection against poaching of fish. Indian major carps are grown in these ponds for fish culture to sustain the rural population. In Bangladesh, the best result has been achieved if the surface area of the substrate is equal to approximately 50-100% of the pond's surface area. The technology seems to hold promise for the farming of any herbivorous fish which is capable of harvesting periphyton from substrates.

Organic matter conservation: Integration of aquaculture within farming landscapes can present further opportunities to enhance carbon sequestration. Using sludge produced during the treatment of aquaculture wastewater to fertilise agricultural crops has been widely advocated and tested to a limited extent (Bergheim *et al*., 1998; Chen, 1998). Sludge and wastewater from aquaculture facilities have also been proposed as soil conditioners for degraded sites and production enhancing inputs to other aquatic systems.

***Green manures and fodder crops*:** Duckweed cultivation has been proposed as a useful intermediate step in transforming unexploited inorganic nutrients in wastewater into fodder and as a component of integrated aquaculture systems, improving resource use efficiency and contributing to more stable culture conditions (Skillicorn *et al*., 1993; Bunting, 1995; Alaerts *et al*., 1996; Iqbal, 1999; Azim and Wahab, 2003). The resulting biomass can be fed directly to herbivorous fish species and livestock or dried and added to formulated feeds for fish, poultry, waterfowl and livestock.

Therefore, in certain cases where carbon sequestration is a priority, it might be better to opt for a phytoplankton-based strategy, although the decision should also be influenced by the options available for the long-term storage of carbon sequestered in this way.

***Wetland restoration and protection*:** Land use change like wetland restoration in agricultural systems has the potential of accumulating of 0.4 t ha^{-1} y^{-1} of carbon (IPCC, 2000). As with terrestrial farming, there may be opportunities for aquaculture operators to restore wetland areas and make a commitment not to convert existing wetlands for further aquaculture development.

Conclusion

It is no coincidence that poverty and food insecurity are highest where water productivity is lowest. Getting more value from water through higher yields, crop diversifications, and integrating livestock fisheries, is an effective way of improving rural income, alleviating poverty and reducing risk by diversifying income sources, thereby improving community resilience and reducing environmental degradation that exacerbates climate change. At global scale, improved productivity helps to reduce greenhouse gas (GHG) emissions by curbing the need to convert land.

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Methane Emission from Livestock and Management Options

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Among domesticated animals ruminants occupy a unique position in human food chain due to their capacity to convert indigestible cellulosic materials for human beings into useful products like milk, meat, etc. It is achieved by the anaerobic fermentation in the animal stomach which harbors a large number of micro-organisms which include bacteria, protozoa, and fungi. The main end products of fermentation of feed in the rumen are short chain fatty acids (SCFA), microbial cells, carbon dioxide and methane. SCFA including acetate, propionate and butyrate are the primary energy substrates for ruminants. Methane on the other hand is the by-product of the fermentation process which is not utilized by the animals and is released in the air. Livestock activities emit considerable amounts of CO_2,CH_4 and N_2O. Direct emission from livestock comes from respiratory process of all animals in the form of CO_2. Ruminants to a major extent and monogastrics to some extent emit CH_4 either as eructation or flatus as part of their digestive process which involves microbial fermentation of feeds.

Methane production has assumed significance due to its role as a greenhouse gas. The evidence showed that methane (CH_4) concentration has been increasing at a rate between 0.7 to 1% per year (Crutzen, 1995) and domestic ruminants are said to be responsible for 12.5% of global methane emission. Methane emission levels from a source can vary significantly from one country or region to another, depending on many factors such as climate, industrial and agricultural production characteristics, energy types and usage, waste management practices, etc. For example, temperature and moisture have a significant effect on the anaerobic digestion process, which is one of the key biological processes that cause methane emissions in both human-related and natural sources.

Source of methane production

Methane, also known as marsh gas is most abundant organic gas in the earth's atmosphere. Methane (CH_4) is emitted from a variety of both human-related (anthropogenic) and natural sources. Human-related activities include fossil fuel production, animal husbandry (enteric fermentation in livestock and manure management), rice cultivation, biomass burning, and waste management. These activities release significant quantities of methane to the atmosphere. It is estimated that more than 50% of global methane emissions are related to human activities. Natural sources of methane include wetlands, gas hydrates, permafrost, termites, oceans, freshwater bodies, non-wetland soils, and other sources such as wildfires.

Global contribution of CH_4 and N_2O emissions from agriculture

In 2005, agriculture contributed for an estimated emission of 5.1 to 6.1 Gt CO_2 eq (10-12% of total global anthropogenic emission of greenhouse gases). CH_4 contributed 3.3 Gt CO_2 eq and N_2O 2.8 Gt CO_2 eq. of global anthropogenic emissions in 2005 agriculture accounted for about 60% N_2O and 50% CH_4. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with net CO_2 emissions of only around 0.04 Gt CO_2 eq (Smith *et al.*, 2007). It is evident from above data that CH_4 and N_2O is the main greenhouse gases are to be taken care of from agricultural sectors. Emissions from soil and associated N inputs, such as synthetic fertilizer, animal manure and crop residues are the main agricultural N_2O sources contributing 90%, with emissions from animal manure stores contributing the rest. CH_4 emission as a share of total agricultural greenhouse gas emissions slightly declined (44% vs 42%) over the 1990s, largely attributing to greenhouse gas emissions from livestock farming (OECD, 2008). Mosier *et al.* (1998) estimated that animal manure applied on soil contributed directly 0.3 Gt CO_2 eq year $^{-1}$ (10%) global N_2O emissions. Another estimate indicates that direct emissions resulting from animal manure application is 0.2 Gt CO_2 eq year $^{-1}$ (IFA/FAO, 2001).

Factors affecting methane production in livestock

Enteric fermentation is the main source of methane production in livestock. The production of methane is a direct loss of digestible energy from the diet. The rate of methane production is affected by animal species, quality and quantity of feedstuffs, body weight, age, exercise etc. It also varies among animal species as well as between individuals of the same species.

Digestive system

Ruminant livestock include cattle, sheep, goats, etc. Unlike monogastrics such as swine and poultry, ruminants have a four compartment stomach (rumen, reticulum, omasum, and abomasum) designed to digest high fiber feedstuffs and provide precursors for energy for the animal to use. Rumen is the largest compartment acts as a fermentation vat by hosting microbial fermentation. About 50 to 65 percent of starch and soluble sugar consumed is digested in the rumen. Rumen microorganisms (primarily bacteria) digest cellulose from plant cell walls, digest complex starch, synthesize protein from non-protein nitrogen, and synthesize B vitamins and vitamin K. Rumen pH typically ranges from 6.5 to 6.8. The rumen environment is anaerobic (without oxygen). Gases produced in the rumen include carbon dioxide, methane, and hydrogen sulfide. The gas fraction rises to the top of the rumen above the liquid fraction. The abomasum is the “true stomach” of a ruminant similar to non-ruminant.

Ruminants eat rapidly, swallowing much of their feedstuffs without chewing it sufficiently. The esophagus functions bi-directionally in ruminants, allowing them to regurgitate their cud for further chewing, if necessary. The process of rumination or “chewing the cud” is where forage and other feedstuffs are forced back to the mouth for further chewing and mixing with saliva. This cud is then swallowed again and passed into the reticulum. Then the solid portion slowly moves into the rumen for fermentation, while most of the liquid portion rapidly moves from the reticulorumen into the omasum and then abomasum. The solid portion left behind in the rumen typically remains for up to 48 hours and forms a dense mat in the rumen, where microbes can use the fibrous feedstuffs to make precursors for energy.

Rumen Environment

Rumen is a complex fermentation vat that harbors highly diversified rumen microbial ecosystem consisting of bacteria (1010 -10 11 cells ml^{-1}, representing more than 50 genera), ciliate protozoa (104 - 106 ml^{-1} from 25 genera), anaerobic fungi (103 - 105 zoospores ml^{-1}, representing from 5 genera) and bacteriophases (108 – 109 ml^{-1} and even more) (Kamra, 2005). The synergism and antagonism among different microbial groups leads to bioconversion of a wide variety of feeds into such form that can be utilized by the animal. The complex anaerobic ecological system of rumen based on numerous biochemical reactions and mutual relationship between number of organisms living in the rumen and their relation with the host animal. Rumen is a capacious fermentation chamber contains large quantity of liquid, having buffering capacity with stable pH and temperature. It maintains in anaerobic environment for development of specific microorganisms. Fermentation reaction is the most important biochemical reaction in the rumen, involves whole enzymatic decay process of the organic substances to different products under anaerobic condition. Fodder contents are transformed during fermentation into useful products like volatile fatty acids, bacterial protein, and group B vitamins. Rumen is the first compartment of digestive system and all food passes through this and is subjected to a complex microbial degradation. The fermentation byproducts mainly ammonia, carbon dioxide and volatile fatty acids (acetic, propionic and butyric acids normal proportions 70:20:10) are taken up by a variety of bacteria, protozoa and fungi that follow a different but interacting pathways. A large amount of hydrogen is produced during the formation of volatile fatty acids in the rumen, which if not removed may inhibit the conversion of NADH2 to NAD (energy conversion mechanism). The symbiosis between bacteria that ferment carbohydrate and the methanogens resulted formation of methane that acts as hydrogen sink and is inevitably vented out in the atmosphere.

Methanogenesis in livestock

Methane production is an integral part of anaerobic fermentation in the rumen (Bryant, 1979; Demeyer and Tamminga, 1987) helping in the removal of hydrogen from the system to avoid its fermentation rate limiting effect.The most common bacteria involved in methane production in the rumen are Methanobacterium ruminantium, M. formicicum, M. ruminatum, Methanobrevibactor ruminantium, Methanomicrobium mobile. Methanogens have symbiotic relationship with rumen protozoa which provides regular supply of hydrogen for methane formation. Methane is a hydrogen sink in rumen eco-system. Alternate hydrogen sinks are propionic acid, unsaturated fatty acids, sulphate and nitrate reduction and reductive acetogenesis. Sulphate and nitrogen is accompanied with production of toxic substances like H_2S and nitrite. Saturation of fatty acid in the rumen is also of minor significance. The amount of total metabolic hydrogen used in the biohydrogination of endogenous fatty acid is only 1% compared to 48% of methane, 33% of VFA and 12% of bacterial cell synthesis (Czerkawski, 1969). It has been estimated that a cow producing 90 kg of methane per year, diversion of hydrogen from methanogenesis to biohydrogenation of fatty acids even if, microbiologically feasible, would require feeding of more than 4 kg of unsaturated fat per day (Weimer, 1998).

Process	Overall reactions	Comments
Methanogenesis	$4H_2 + CO_2 \rightarrow CH_4 + H_2O$ $CH_3COO^- + H^+ \rightarrow CH_4 + H_2O$	Ruminal methane synthesis
Sulphate reduction	$4H_2 + 2H^+ + SO_4 \rightarrow H_2S + 4H_2O$	Not significant in rumen
Nitrate reduction	$4H_2 + 2H^+ + NO_3 \rightarrow NH_4 + 3H_2O$	Undesirable in rumen owing to accumulation of toxic nitrate
Reductive acetogenesis	$4H_2 + 3CO_2 \rightarrow CH_3COO^- + H^+$	Desirable but not significant ruminal reaction
Biohydrogenation of fatty acids	$CH_2 = CH + 2H^+ \rightarrow -CH_2 - CH_2$	Of minor significance as hydrogen sink in the rumen

Adopted from: Weimer (1998)

Animal population

The 18th livestock census conducted during 2007 by Govt. of India results have revealed that there is livestock population of about 485 million, out of which 283 million are bovines and the rest are mainly sheep, goats, pigs and other animals. The bovine population consists of 161 million indigenous cattle, 25 million crossbred cattle and 98 million buffaloes. The census data established that there is a shift towards high milk yielding animals. The number of high yielding cattle and buffaloes are increasing and there is declination in the population of indigenous cattle. Poultry population has also increased at a very high rate between the last two censuses. The domestic animal populations increased by 0.5 to 2.0 percent per year during the last century, according to the Environmental Protection Agency (EPA) report Policy Options for Stabilizing Global Climate (Lashof and Tirpak, 1990). These population increases have become a significant source of atmospheric methane and domestic animals currently account for about 15 percent of the annual anthropogenic methane emissions. The production rate is affected by factors such as quantity and quality of feed, body weight, age, and exercise, and varies among animal species as well as among individuals of the same species.

Animal requirement and Feed intake

The dry matter intake of individual animal varies depending upon body size and physiological activity. Adult animals require minimum energy to maintain their body function and at normal condition when adult animals are on total rest 6-7% energy in the form of methane is lost. At maintenance level the methane production in domestic ruminant (cattle, sheep, and goat) or herbivores is more compared to monogastric. Methane release rate by ruminants were lower when fed with protein-rich diets and high when fed with crude fibre. Blaxter and Clapperton (1965) have shown that methane production by cows and sheep at maintenance level increased from 7.5 to 9% when digestibility of feed was raised from 65 % to 95%. However, the methane yield (6.5 -7%) was independent of digestibility while animals were fed twice the maintenance level and decreased from 6% to 5% when they were fed at three times maintenance level with 90% digestibility. Similar findings were reported by Van der Honing *et al.* (1981). Krishna *et al.* (1978) reported higher yields of 9% CH_4 in cattle fed on slightly above maintenance diet and low quality feed. Methane production (% gross energy intake) from Indian livestock on wheat straw based ration in buffalo and cattle 4 to 9%, sheep and goat between 3 -7% has been reported from different workers. Methane productions in sheep show a larger range of values. Murray *et al.* (1978) observed CH_4 yield from 3.5% to 5.6% with increasing feed intake in Marino sheep with protein rich diet while Seeley *et al.* (1969) measured 8.2 to 9.7% in adult sheep fed on ryegrass hay. Considerable variation in proportion of methane production in sheep fed on wheat straw, which ranged between 35 to more than 60 litre kg $^{-1}$ digested organic matter intake (Bluemmel *et. al.*, 2005).

Methane emission was found greater in cows compared to sheep and deer on similar diet indicating that there are differences between ruminant species. However, methane emission are also influenced by the size of the animal, quantity of feed consumed and efficiency by which animals convert feed to useful products. Ruminants are relatively fed poor quality forage may be deficient in number of essential micronutrient required for microbial growth. Number of reports clearly indicated that supplementation of deficient nutrients has been found increasing productivity through efficiency of feed utilization.

The methane production from pigs on highly digestible fattening feeds is less than 1% of the gross energy intake. Pigs given low quality feeds commonly kitchen waste and green fodders are expected to yield approximately 2%. Methane yield from horse are between pigs and ruminants. They equal 3-4% of the digestible energy or 2-3% of the gross energy intake.

Methane is a direct loss of feed carbon and energy to rumen microbes and host animal alike. Production of methane is closely related to total and digestible organic matter intake. Besides intake and digestibility, the kind of fermentation products, overall partitioning of digested feed between microbial biomass and short chain fatty acids (SCFA) and within acetate, butyrate and propionate ratio play an important role in methane production (Leng, 1993). Methane is produced with acetate and butyrate and not with propionate (Wolin, 1960). Level of feed intake over maintenance and the digestibility of feed affect rate of CH_4 production. In livestock average methane loss is estimated to be 2 -12% of the gross energy intake. Hungate (1966) reported that 500 kg cow produces about 800 liters of hydrogen which gives rise to 200 liters of methane per day. Czerkawski (1969) calculated total methane emission from ruminant livestock in different countries on assumption that cattle, sheep and goat produces 250, 40 and 30 liters per day, respectively. Khan *et al.* (1996) reported that buffalo at maintenance level of feeding on wheat straw based rations produced only about 150 liters methane per day. Equation formulated for CH_4 prediction from ruminant livestock for the National GHG inventory is $Y = -17.766 + 42.793X - 0.849X$ where Y is CH_4 production (litre day $^{-1}$) and X is DMI (kg day $^{-1}$).

Strategies to reduce methane production from livestock

There has been a lot of research conducted in both developed and developing countries on strategies to reduce methane emission from domestic animals. The main focus has been to improve production efficiency either by genetic improvement or through nutritional strategies in order to reduce loss of energy in the form of methane. Since any reduction in methane production has the potential to improve production efficiency of the animal through increased availability of digested energy for productive purpose (milk, meat, drought energy).

Genetic selection of low and high methane emitters

Search for quantitative trait loci (QTL) for methane emissions is a challenging job. Since, methane emission is not primarily directed by the ruminant, methane is produced by the microbes living inside the ruminant and hence the role the animal itself plays is not direct, but rather mediates the interaction between the host and the microbe. Hence, the genetic signal is unlikely to be obvious and direct, and more likely to be diffused. Methane emission is a challenging ‘phenotype’ to establish. Unlike more obvious physical traits, the trait of methane emission varies with time, forage quantity and quality, age of the animal and varies between animals. For the long term approach, genetic selections of cows that have improved feed efficiency have a possible option.

Manipulation of rumen microbes

Modification of rumen microbial composition and their activity by using chemical additives, introduction of naturally occurring or genetically modified foreign microbes into the rumen and genetic manipulation of existing microbes in the rumen ecosystem has been tried. Interspecies trans-inoculation of rumen microbes was also successfully used for annulment of dietary toxic factor.

There are several novel approaches to reduce CH_4 that are not very practical at present such as defaunation of the rumen. Defaunation of cattle, buffalo (Santra *et al.,* 1994) and sheep (Chandramoni, 1997, Chandramoni *et al.*, 2001) for reducing methane production and increasing protein outflow in the intestine, resulted in improved growth and feed conversion efficiency of the animals. Encouraging acetogenic bacteria to grow so that they can perform the function of removing hydrogen instead of methanogens is also an alternate method. Research is also being conducted to develop vaccine, which stimulates antibodies in the animal against the methanogenic bacteria active in the rumen.

Reduction of ruminal methanogenesis

Methane is a hydrogen sink in rumen eco-system. Alternate hydrogen sinks are propionic acid, unsaturated fatty acids, sulphate and nitrate reduction and reductive acetogenesis. Dietary encapsulated fumeric acid reduced methane formation by 76% in growing lambs fumerate and malate (dicarboxylic acid) naturally found in plants have been found to stimulate hydrogen use for propionate synthesis (Aluwong *et al.,* 2011). Dietary fats have the potential to reduce methane upto 37%. Saturation of fatty acid in the rumen is also of minor significances. The amount of total metabolic hydrogen used in the bio-hydrogenation of endogenous fatty acid is only 1 per cent compared to 48 percent in methane, 33 per cent in VFA synthesis and 12 per cent in bacterial cell synthesis (Czerkawski, 1969). It has been estimated that a cow producing 90 kg of methane per year, diversion of hydrogen from methanogenesis to biohydrogenation of fatty acids, even if microbiologically feasible, would require feeding of more than 4 kg of unsaturated fats per day (Weimer, 1998).

Dietary strategies to reduce methane production from livestock

Supplementation of critical nutrient

Ruminants are mainly supported on by-products of agriculture or graze forages which are deficient primarily on nitrogen content. Improving feed N and energy utilization through dietary measures without negatively affecting animal productivity is considered a possible way to reduce greenhouse gas emissions through decreased N and energy contents in urine and faeces. Supplementation of deficient nutrient or a mixture such as urea and urea and minerals along with by-pass protein (Saraswat *et al.,* 2001) to straw based rations, alkali treatment of straws and supplementation of urea-molasses-mineral block have been shown to reduce methane production when expressed per kg of meat and milk production. Various strategies to reduce methane production from Indian livestock have been discussed by many authors (Khan, 1994; 1996; 1997; Karma, 1994; Singh, 1997; Haque *et al.*, 2001).

Processing and pretreatment of forages

Grinding and pelleting of forages can reduce methane emission by 40%. Lower methane losses per unit of feed intake have been reported when smaller particle size forage are fed. Treatment of wheat straw with urea or a mixture of urea and calcium hydroxide prior to feeding also reduce methane production per kg organic matter intake (Sahoo *et al.*, 2000).

Identification and feeding of potential grains and cereal byproducts

Replacement of barley with jowar (sorghum) as cereal also reported to significantly reduce methane production in ruminants without any adverse effects on performance parameters (Pattanaik *et al.,* 1998). Moreover, feeding of green sorghum at higher ratio to crossbred calves in wheat straw based diet reported to reduce methane production (Haque *et al.,* 2001).

Addition of naturally occurring defaunating plants

A significant reduction in protozoal count (74.7%) and methane production was observed when lambs were fed on oat hay based diet along with condensed tannin (@ 0.05% of total DM intake) obtained from a plant *Uncaria gambir* (Saravanan, 2000). Treatment of wheat straw with urea or urea plus calcium hydroxide significantly reduced methane production (Sahoo *et al.*, 2000).

Use of additives to alter rumen fermentation

Feed additives like rumensin / monensin have been tried to reduce methane production. In vitro incubations have given promising results in reduction of methane production which ranged from 30-35 per cent for dairy cows with medium level of milk production (Singh, 1997). However, rumen microbes adapt to ionophores quickly and methane production in vivo return to pretreatment values within two weeks (Johnson and Johnson, 1995). Saravanan (2000) observed a substantial reduction (89.1%) in methane production on feeding 0.14g bromochloromethane per lamb along with a plant (*Uncaria gambir*) extract containing about 50 percent condensed tannins. Roughage as well as concentrate based rations supplemented with soapberry fruit-mango-steen peel pellets containing condensed tannins and saponins caused changes in ruminal micro organisms and their fermentation end products resulting into decreased methane production (Onanong *et al.*, 2009). Halogenated methane analogues have also been tired to reduce methane production from animals with variable result.

A number of papers have addressed methane mitigation options for ruminant animals. Some of these mitigation strategies are toxic to the rumen microbes and the animal and also some have short lived effects due to microbial adaptation, volatile in nature, expensive or the delivery system of these additives have limitations in implementation. There is growing appreciation that efficiency of feed utilization per unit of production of meat, milk, work, etc. can be improved by simple technology inputs. If applied this could have major implications for stabilizing global atmospheric methane concentration.

Table 1. Estimation of methane emission from Indian livestock using Respiration calorimeter

Animal species	B wt	Diet	CH_4% GE	CH_4 (l d^{-1})	Year of estimation
Calf	231	WS +conc.	7.1	197	1995
Calf	265	WS +conc.	5.4	148.5	1995
Cross bred Milch cows	300	Wheat straw based ration	6.0	221	1999
Cross bred	360	WS + con mixt. (100% ME)	6.52	179.3	2001
Cross bred	360	WS + con mixt. (100% ME)	6.8	161.6	2001
Cattle heifer	282	WS + GNC	5.92	100	1987
heifer	338	do	8.36	186	1987
Buffalo	350	WS +oat green	7.3	176	1999
Buffalo	442	WS + GNC	6.4	177	1987
Buffalo	449	WS + conc (100%)	6.62	198	1990
Buffalo	411	WS + conc (80%)	5.59	147	1990
Buffalo	449	WS + conc (60%)	6.27	131	1990
Buffalo	252	WS + conc. + MOC	9.01	125.7	1999
Buffalo	271	WS + conc. + dried poultry droppings	6.56	118.9	1997
Buffalo	279	WS + conc. + dried poultry droppings	6.93	131.2	1997
Buffalo	194	Urea ammoniated WS +conc with fish meal	5.7	116.9	2000
Buffalo	197	Urea ammoniated WS +conc with GNC	5.2	112.8	2000
Buffalo	195	Urea ammoniated WS +conc with formaldehyde treated GNC	6.1	128.2	2000
Buffalo heifer	263	WS +conc with MOC	4.08	120	2001
Buffalo heifer		WS +conc with sunflower	3.93	119	2001
Buffalo heifer		WS +conc with soyabean cake	4.64	143	2001
Sheep	41.4	WS supplemented with urea	3.71	10	2000
Sheep	43.7	Urea ammoniated WS	3.17	11	2000
Sheep	13	WS +oat green	7.7	14	2000
Goat	20	Oat hah	6.94	12.6	1986
Goat		Oat hay + conc with salseed	6.73	16.93	1986
Goat		Oat hay + conc	7.51	16.5	1986
Goat	20	Berseem + conc	5.2	15.58	1997

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Dynamics of Carbon Flow in Aquatic Ecosystem and Management Options

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Introduction

The organic carbon, comprising living and non-living fractions, is instrumental for the flow of energy and trophic structure of aquatic ecosystems (Wetzel, 2001). Although high concentrations of organic carbon are generally undesirable in any aquatic ecosystem due to the formation of disinfection byproducts (Amy *et al*., 1990), nevertheless, at low concentrations it may be beneficial and even essential for aquatic ecosystems. Understanding the ecosystem processes of organic carbon in the water bodies is important because any action to manage the concentrations of organic carbon in fish culture ponds and subsequent intakes by fish might lead to potential ecological and human hazards. For evaluating the role of organic carbon in ecological processes, the organic carbon may be divided into three groups i.e., dissolved, particulate and bio-available forms. However, the formation of disinfection byproducts during water treatment is generally not directly related to these forms, but is a function of the chemical structure and reactivity of the organic carbon.

Organic carbon cycling transportation

The cycling of organic carbon in terrestrial environments is shown in schematic form in Fig. 1. Organic carbon is produced from atmospheric carbon dioxide and water by plants through many complex reactions of photosynthesis (in forests, crop land, range land, and to a lesser degree on urban land). Organic carbon enters the surface soil pool following senescence and litter fall of plant matter. Microbial populations and fungi break down this organic carbon into smaller, more labile forms and ultimately to carbon dioxide. A fraction of soil organic matter is stored in the terrestrial compartment and a fraction is transported in surface runoff and into groundwater which may enter surface waters as base flow. The magnitude of organic carbon export is a function of the land use and the level of rainfall and runoff. Literature suggests a range of dissolved organic carbon exports from 0.38 tons km^{-2} yr^{-1} for cool grasslands to 9.9 tons km^{-2} yr^{-1} in swamp forests (Aitkenhead and McDowell, 2000). For most freshwater bodies, watershed sources of organic carbon are much greater sources than internal production (Wetzel, 2001). Other things being equal, dry regions are expected to export lower amount of organic carbon than wet regions with greater runoff. This is relevant to the Northeastern region of India because it exhibits a wide precipitation characteristic, with most of the regions being wetter than the rest of the India.

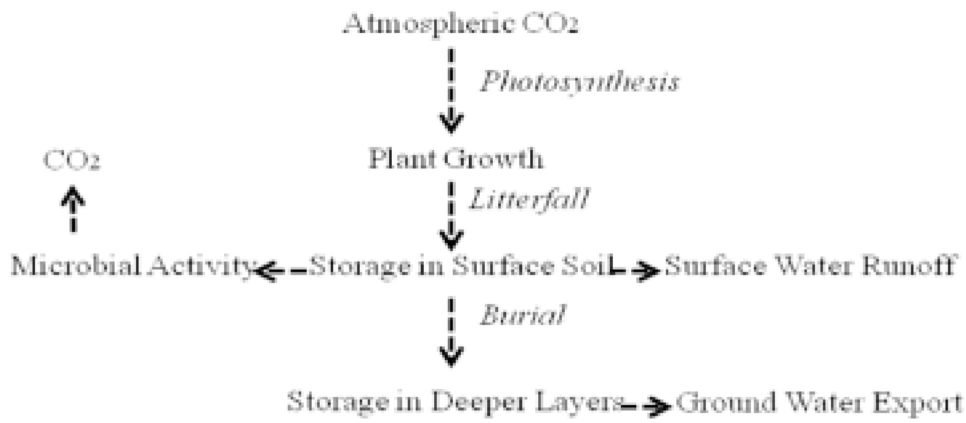

Fig 1 Schematic diagram of organic carbon cycling in the terrestrial environment

The cycling of organic carbon in the aquatic environment is shown in schematic form in Fig.2. Organic carbon may enter into a water body from terrestrial sources in the watershed as shown in Figure 2, and it may also be photosynthesized within the water body by benthic and planktonic algae and aquatic plants, using atmospheric carbon dioxide or dissolved inorganic carbon as a carbon source. For simplicity, the organic carbon is represented as two pools, particulate and dissolved organic carbon (POC and DOC, respectively), although in reality, there is a continuum of particle size and molecular weight that influences its metabolism (Wetzel, 2001). A key feature shown in Figure 2 is that DOC unlike POC, can not be directly taken up by primary consumers. Bacteria may convert DOC to bacterial biomass which then becomes available for consumption by higher organisms like fishes (Wetzel, 2001; Jassby and Cloern, 2000). POC from the ponds and POC from aquatic primary production are generally more accessible to the food web than DOC. In most ecosystems, it has been observed that the detrital organic carbon (as DOC and non-living POC) is far more abundant than the organic carbon in living POC (Wetzel, 2001). Bacteria may also metabolize DOC to carbon dioxide that exitsion the aquatic system. The atmospheric pathway for loss of organic carbon is significant, and in some areas of the Delta, such as the islands, can be far in excess of aqueous export (Deverel and Rojstaczer, 1996). Aged sediments in water bodies play a key role in the cycling of organic carbon. Generally, POC can settle in the sediments, and provide a source of DOC to the overlying water column through microbial decay. Sediment POC can be stored for long periods, or may be scoured and transported downstream and/or low lying areas during high flow events. Thus, during the wet season, large quantities of organic carbon that might have accumulated in the sediments in the preceding months or years, enters water bodies through streams in drainage and runoff and through groundwater flows. Streams play a critical role in organic carbon transport. They act as conduits for organic carbon exported from land surfaces, but may also convert some of the organic carbon into carbon dioxide or store it in sediments. At other times, depending on flow rates, sediment erosion or efflux can be a contribution to the transport load. Further, streams may be an additional source of organic carbon production through algal and macrophyte growth. Organic carbon transport in streams is controlled by flow rates with the greatest loads being transported during high flow events in the wet season. In the wet season, especially during storm flows or high flood, organic carbon stored in the surface layers of various land uses, and also in stream sediments is transported into downstream waters, especially, to the beels and reservoirs.The reservoirs in upland areas and hill streams play important role in organic carbon production and export. Reservoirs, by storing water for extended storage times during the warm, dry months of the year and by providing a large surface area, may provide an environment for algae growth. Some of the organic carbon produced in the reservoirs may

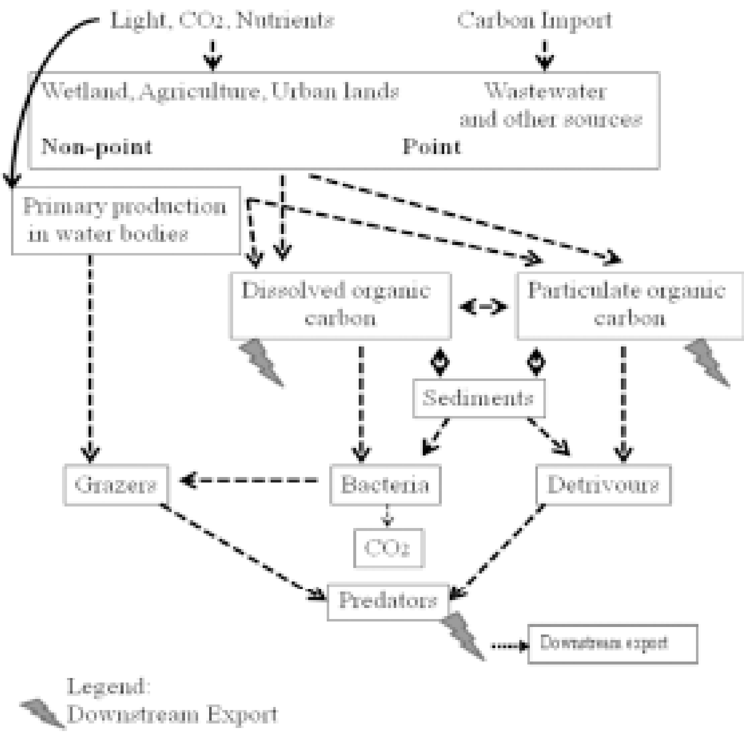

Fig 2 Schematic diagram of organic carbon cycling in the aquatic environment
(Modified from: Wetzel, 2001)

also be exported downstream and get accumulated in low lying fish culture ponds. Conversely, low land paddy fields and fish culture ponds may act as large settling basins for POC, resulting in less transport of organic carbon. Tributary organic carbon loads (termed allochthonous loads), which include detrital as well as planktonic organic carbon, reach the low laying areas where the residence time ranges from days to weeks, depending on season and inflow volume. As shown in Figure 3, the upland area is itself a producer of organic carbon due to primary production by benthic and planktonic algae and plants and export from tidal marshes, agriculture, and developed lands (autochthonous loads). A fraction of the internally generated and the tributary organic carbon is exported to the downstreams. Organic carbon is also lost from the upland areas by the diversion of water at the water intakes for further uses in fish culture. Additionally, organic carbon is incorporated in sediments and metabolized to carbon dioxide. Because large water intakes are located in the Delta, the quality and quantity of the autochthonous organic carbon is of particular relevance to potential water quality impacts. Decline in fish species and related food web impacts on downstreams and the uplands have motivated studies of organic carbon sources and bioavailability independent of drinking water quality-related investigations. Driven by variations in tributary inflows, allochthonous organic carbon loads vary widely from year to year (Jassby *et al*., 2002). There is also a substantial year-to-year variation in primary production in the Delta with a declining trend in primary production in recent years that is attributed to various causes including the consumption of phytoplankton by an exotic invading species (the Asian clam, *Potamocorbula amurensis*) and other benthic consumers. Recent studies have concluded that tributary inputs of organic carbon are several times larger than that in-Delta primary productivity and agricultural drainage (Jassby and Cloern, 2000). A fraction of the tributary and internal loads are exported to the water supply intakes, while the remainder flows into San Francisco Bay. Evaluation of bacterial communities in the Delta using DNA fingerprints showed seasonal, but not spatial variation, in the bacterial communities. Bacterial communities associated with local primary production-derived organic carbon were dominant in summer/fall, and communities associated with terrestrial sources were dominant in winter (Stepanauskas *et al*., 2002). The bioavailability, and the ecological significance of different components of organic carbon in the upland area are variable. Although a fraction of the DOC is available for bacterial metabolism, it appears to be less important food source at the base of the food web than organic carbon derived from primary production within the upland/hilly areas (Jassby and Cloern, 2000). Further, much of the natural POC load in the tributaries is much poorer food source than natural phytoplankton. In controlled experimental studies with a zooplankton, *Daphnia magna*, total detrital organic carbon concentrations were found to be weakly related to growth, although chlorophyll concentrations were found to be a good predictor for growth (Müeller-Solger *et al*., 2002). The study indicated that in a system like the Delta with abundance of detrital organic carbon, some organisms exhibit a preference for organic carbon freshly derived from primary production. In laboratory studies on water samples from the upland water bodies, it has been shown that a relatively small fraction of the DOC and POC is available for bacterial metabolism (operationally defined as a 21-day incubation), and the bioavailable fraction is well correlated with primary production (Sobczak *et al*., 2005). If these results are corroborated by further research, potential reductions in tributary loads of organic carbon are less likely to have adverse ecological impacts, and it may be found that water quality objectives for fish culture and ecosystem health are not necessarily in conflict.

Organic carbon originates in upstream natural sources, and is released from reservoirs to the lower fish culture ponds/watershed, where there are additional contributions from point and non-point sources. A fraction of the organic carbon is exported in aquaducts, but in most seasons, a large fraction is exported downstream (Source: Carbon flow model in San Francisco Bay).

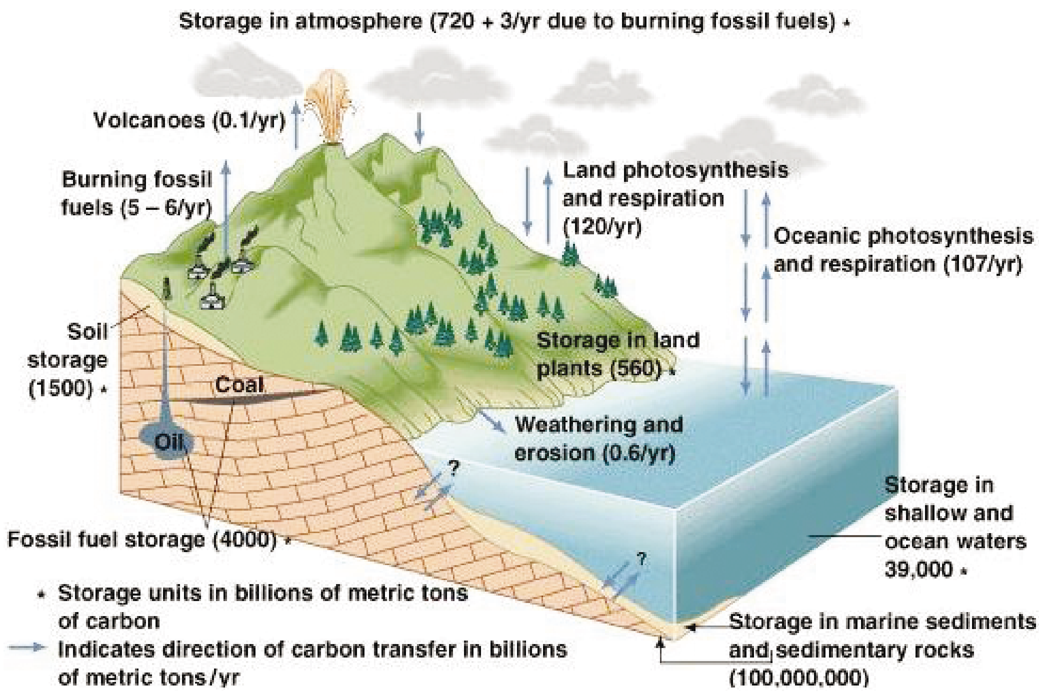

Fig 3 Schematic representation of organic carbon transport in the hill ecosystem

Carbon is one of the major biogeochemical components in the environment. The carbon cycle (Fig 4) describes the flow of essential elements from the environment to the living organisms and back to the environment again. This process is required for the building of all organic compounds and involves the participation of many of the earth's key forces.

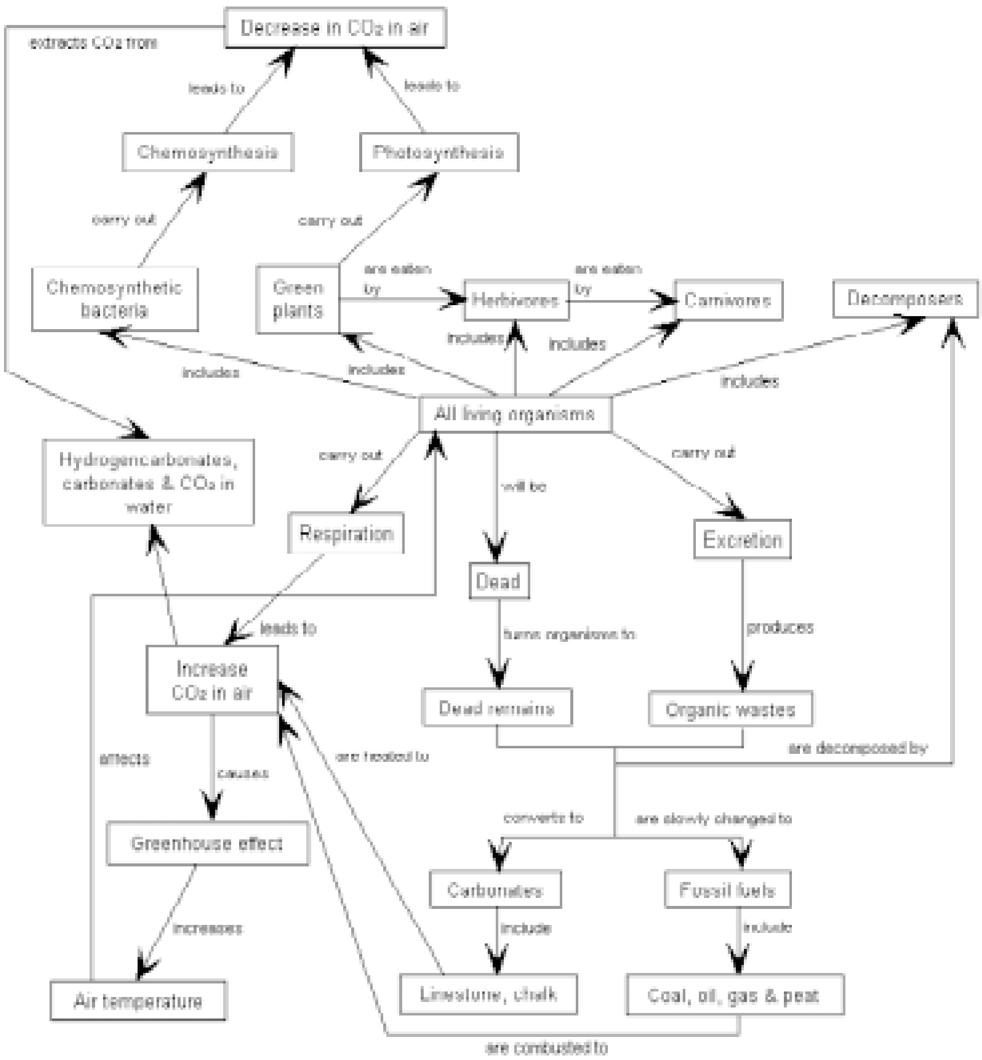

Fig 4 The carbon flow cycle

Conclusion

The carbon cycle has affected the earth throughout its history; it has contributed to major climatic changes, and facilitated the evolution of life. Organic carbon in the dissolved form (DOC) is the form considered to be more likely to react during chlorination and from disinfection byproduct compounds. DOC is generally less bioavailable to the base of the food web compared with particulate organic carbon and/or organic carbon freshly derived from primary production. Thus, water bodies located in hilly areas and to control or manage DOC levels for fish culture practice in those areas may not have direct adverse effects on the food web, although this is a subject that needs to be investigated precisely. Further, characterization of organic matter through sophisticated analytical tools such as stable isotope signatures, is an active area of research. There is limited knowledge on the relative propensity of different sources to form disinfectant byproducts, although it appears that plain land drainage is somewhat less reactive than hilly drainage and its tributary sources.

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Role of Biochar in Carbon Sequestration

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Introduction

Earth's atmosphere contains carbon dioxide (CO_2) and other greenhouse gases (GHGs) which are very important because it acts as a protective layer causing our planet to be warmer than it would otherwise be and make the earth suitable to live in (preposition). If the level of CO_2 and GHGs rises, mean global temperatures are also expected to rise as increasing amounts of solar radiation are trapped inside the layer. However, the level of CO_2 in the atmosphere is determined by a continuous flow among the stores of carbon in the atmosphere, the ocean, the earth's biological systems, and its geological materials. As long as the amount of carbon flowing into the atmosphere (as CO_2) and out (in the form of plant material and dissolved carbon) are in balance, the level of carbon in the atmosphere remains constant. Human activities particularly the extraction and burning of fossil fuels and the depletion of forests are disturbing the cycles of CO_2, hence increasing the level of GHGs (primarily CO_2) in the atmosphere (IPCC-WG1, 2007). It is estimated that world energy need will contribute 35.2 billion metric tons of CO_2 by 2020 and 43.2 billion metric tons by 2035 as compared to 30.2 billion metric tons in 2008 - an increase of 43 percent over the projection period (USEIA, 2011). These slow but steady increases of CO_2 in the atmospheres cause the rise in global temperature thus resulting in climate change.

Before the level of GHGs reaches a level not safe for human survival, it is necessary to take preventive measures. For mitigating the risk of global climate change, we generally have focused on reducing emissions of carbon dioxide and other greenhouse gases (GHGs). However, much less attention has been given to the potential for storing the significant amounts of carbon in soil, forests and other ecosystems. This certainly might be an alternative means of offsetting the effect of emissions on GHGs concentrations in the atmosphere. Removing carbon from the atmosphere and depositing it in a reservoir (capturing of carbon dioxide) is called carbon sequestration and soils are among the largest reservoir, of carbon. Hence, soil may act as a potential sink for carbon and accumulate carbon from atmosphere. In other words, soil carbon sequestration may be defined as transferring atmospheric CO_2 into long lived pools in soil and storing it securely so that it cannot be immediately remitted. In a simple term, increasing soil carbon stock through proper land and crop management practices is called carbon sequestration or soil carbon sequestration (Lal *et al.,* 1998).

Soil organic carbon (SOC) which is the key component of soil organic matter (SOM), is the central element of soil fertility as well as productivity. Maintaining and improving of SOM or SOC is prerequisite to ensuring soil quality, future productivity, and sustainability of agricultural system (Katyal *et al*., 2001). The SOM not only affects sustainability of agricultural ecosystems, but also extremely important in maintaining overall quality of environment as soil contains a significant part of global carbon stock. Hence, there is a growing interest in assessing the role of soil as a sink for carbon under different agricultural management practices and land uses, because some estimates show that increase in soil organic carbon (SOC) content by 0.01% could lead to the C-sequestration equal to the annual increase of atmospheric CO_2-C (Lal *et al*., 1998).

Long duration storage of carbon in soil has been considered as an important method to control increasing level of CO_2 concentration in the atmosphere (Lal, 2009). From the Amazonians' primitive technology, called "Terra-Preta" of enhancing soil productivity with charred biomass, biochar has emerged as a viable technique for carbon sequestration in soil (Lehmann *et al.,* 2006).

Biochar and carbon sequestration

Biochar (Fig 1) is a carbon reach material produced by incomplete combustion of biological materials in absence of oxygen or with limited amount of oxygen. It is believed that biochar can store carbon in soil for hundreds to thousands of years and thus level of green house gases like CO_2 and methane can be reduced significantly (Lehmann, 2007).

Fig 1 Maize stalk derived biochar

Biological carbon cycle involves two major processes – photosynthesis and respiration. In photosynthesis, plants absorb atmospheric CO_2 and produce biological mass and in respiration, biomass is converted to CO_2 (Fig 2). Production of CO_2 is also largely contributed by decomposition of dead plant cell and fire. In undisturbed forest ecosystem, the cycle of uptake of carbon by photosynthesis and release by decay is balanced (Steiner, 2008). This balance is disturbed when fuel and biomass are completely burnt causing a sudden release of huge amount of C, which took thousands of years to accumulate in the form of CO_2 and other C-compounds in the atmosphere.

Figure 3 is an illustration of the manipulated carbon cycle due to biochar carbon sequestration and carbon negative energy production. Biochar being a pure form of carbon does not decompose easily and remains in the soil for thousands of years. Thus pyrolysis of

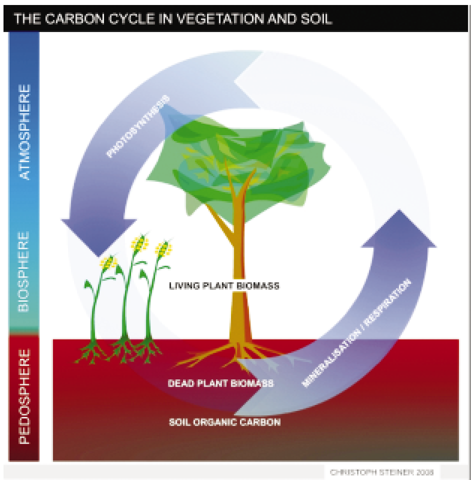

Fig 2 Simple carbon cycle

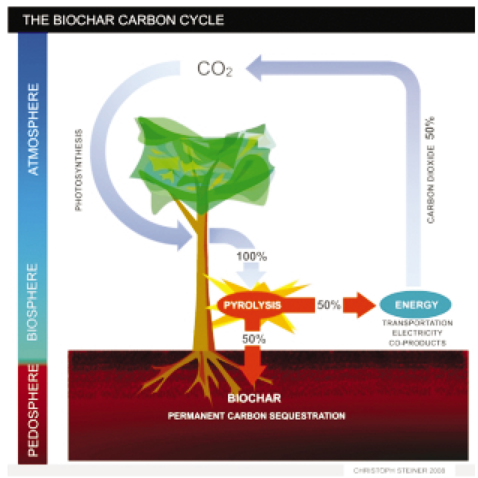

Fig 3 Biochar carbon cycle

(Source: Steiner, 2008)

biomass can transfer 50% of the carbon stored in plant tissue from the active to an inactive carbon pool. The remaining 50% of carbon can be used to produce energy and fuels. This enables carbon negative energy generation if re-growing resources are used i.e., with every unit of energy produced, some amount of CO_2 is removed from the atmosphere (Steiner, 2008).

After charring, approximately 50% of the C in biomass is left as stable biochar residue and another 50% is released immediately while the non-burnt biomass decompose slowly over time but continue releasing leaving only 10-20% C in agricultural soil after 5-10 years. This shows that by applying biochar in soil more C can be left in soil than applying non-charred biomass (Fig 4).

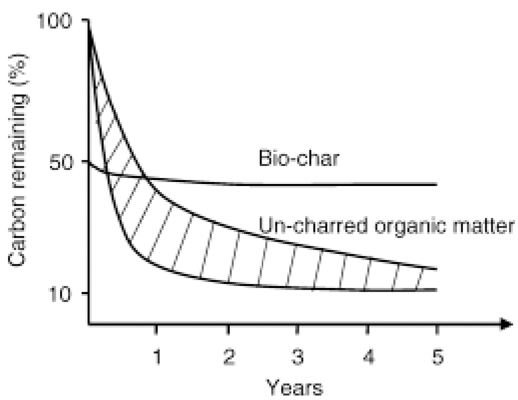

Fig 4 Decomposition pattern of biochar

(Source: Lehmann *et al.*, 2006)

The systems where biochar can be generated and incorporated into the soil are (i) shifting cultivation (ii) charcoal production (iii) recycling of agricultural wastes (iv) energy production using biomass and (v) cropping for biochar using fast growing trees. In shifting cultivation, instead of “slash-and-burn” the practice should be “slash-and-char” by which a huge amount of C can be sequestered in soil. A significant amount of small sized fine charcoal powder is produced while making charcoal for industrial and household fuel purpose. This part of charcoal can be used as biochar which showed many good results. Many of the agricultural and forest residues are very much suitable for production of biochar. When renewable energy is produced from energy crop or waste biomass by pyrolysis process, biochar is produced as byproduct (Lehmann *et al*., 2006). An estimation of potential carbon recovery from different systems is shown in table 1.

Table1 Potential C recovery in the form of biochar from different

System	Method	Annual C recovery, Teragram (10^{12} g)
Shifting cultivation	Slash and char	190-213
Charcoal production	25% fine particle of actual tradeable charcoal	8
Recycling of agricultural wastes	Pyrolysis	160
Energy production using biomass	Pyrolysis	180

(Source: Lehman *et al*., 2006)

Biochar and soil properties

The global carbon cycle is made up of flows and pools of carbon in the earth's system. The important pools of carbon are terrestrial, atmospheric, oceanic, and geological. The carbon within these pools has varying lifetimes, and there are interflows among them. Carbon in the active carbon pool moves rapidly between pools. In order to decrease carbon in the atmosphere, it is necessary to move it into a passive pool containing stable or inert carbon. Biochar provides a facile flow of carbon from the active pool to the passive pool (Kwapinski *et al*., 2010).

The chemical, physical, morphological and spectral properties of biochar are largely influenced by charring temperature and duration. Increasing temperature and duration decreases the biochar yield and volatile matter content but increases C, K and P contents as well as mean residence time. It was estimated that mean residence time ranges from hundreds to thousands of years and generally increases with charring temperature and duration. Biochar application in soil acts as a conditioner and plays a much more important role in improving crop growth than as a fertilizer itself. The improvement of crop growth may result from an increase of pH and CEC (Peng *et al*., 2011). Apart from the beneficial effects to soil fertility and drawing CO_2 from the atmosphere, bio-char applications to soil are also able to reduce the emissions of other greenhouse gases due to better aeration (less frequent occurrence of anaerobic conditions) and possibly by greater stabilization of C. Biochar applications to soil also have the potential to decrease environmental pollution because bio-char is an efficient adsorber of dissolved ammonium, nitrate, phosphate and other ionic solutes as well as hydrophobic organic pollutants.

Biochar application for environmental management can be invoked for soil improvement, waste management, energy production and climate change mitigation (Whitfield, 2009). Biochar can be used as a soil amendment to improve soil quality (Inyang *et al*., 2010), to increase pH and CEC (Peng *et al*., 2011), to increase in plant growth and yield (Lehmann *et al.,* 2003), improve water quality, increase soil moisture retention, reduce emission of green house gases from soil, reduce leaching of nutrients, reduce soil acidity, reduce irrigation and fertilizer requirements (Steiner *et al*., 2007) and also to reclaim degraded and spoiled land (acidic and alkaline soils) (Whitfield, 2009). For waste water treatment, biochar can be used as a contaminant remediation barrier or a low-cost adsorbent to remove contaminants (Inyang *et al*., 2010).

No information exist at present whether this adsorption behaviour would translate into a significant reduction of non-point source pollution of ground and surface waters by fertilizers or other pollutants in agricultural watersheds. The environmental benefits of biochar applications other than C sequestration are still poorly quantified. In this context biochar applications and uses still needs more research.

Feedstock material for biochar production

Agricultural and forestry residues can be most suitable feedstock for biochar production. Waste is produced in significant amounts from field crop residues such as paddy straw, wheat straw, maize stalk and many other remnants of agricultural crops in the field. Forest residues include logging residues, dead wood, excess saplings, pole trees etc. Substantial amount of residues are produced from saw mills and rice mills which are good material to convert into biochar. Urban wastes like yard trimmings, site clearing, pallets, wood packaging and other industry and municipal residues could potentially be a suitable and quantitatively important source of biochar.

The most suitable materials having high lignin concentration yields the good bio-char (Demirbas, 2004) such as residues from sawmills, forest residues, or nut shells. Other suitable crop residues for biochar production are nut shells (e.g., groundnut, hazelnut, macadamia nut, walnut, chestnut, coconut) and bagasse from sugar cane processing, olive or tobacco waste (Lehmann *et al*., 2006). Some of the agricultural and forestry biomass available near the ICAR Research Complex for NEH Region, selected for making biochar are shown in figure 5.

Biochar production

Biochar is produced by simple pyrolysis technique with little or no oxygen (Fig 6). The process also produces bio-oil and syngas which can be used as a source of renewable fuel. Various forms of agricultural residues, energy crops, wood residues and paper waste are mainly composed of three polymers: cellulose, hemicellulose, and lignin, with small fractions of water, organic extractives, and inorganic materials (ash) (Thomsen *et al*., 2011). Figure 8 shows a schematic pattern of biomass decomposition via pyrolysis.

There are four types of pyrolysis methods for generating biochar which are:

Fig 5 Locally available biomass for making biochar

1. Slow Pyrolysis - traditional (dirty, low char yields) and modern (clean, high char yields)
2. Flash Pyrolysis - modern, high pressure, higher char yields
3. Fast Pyrolysis - modern, maximizes bio-oil production, low char yields
4. Gasification - modern, maximizes bio-gas production, minimizes bio-oil production, low char yields but highly stable, high ash content

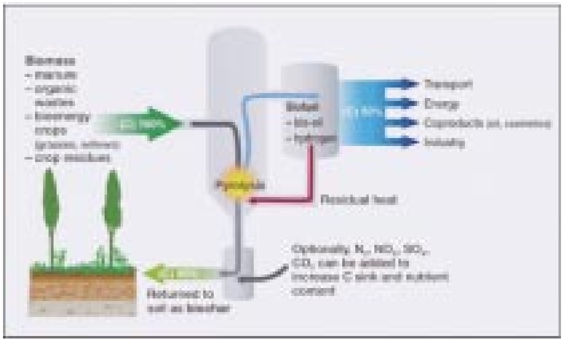

Fig 6 Biochar production process

(Source: Lehmann, 2007)

The slow pyrolysis process technology can be adopted to produce biochar in the agricultural field by a simple charring kiln as shown in figure 7. While experimenting with pine waste, it has been seen that about 25% of the biomass is converted to biochar containing about 65% carbon.

Conclusions

Biochar is most suitable and viable technology for transferring carbon from atmosphere to soil i.e., soil carbon sequestration. It is also a sustainable technology for carbon negative energy production. A huge amount of carbon can be stored in soil by converting agricultural and forestry residues and wastes to biochar through simple pyrolysis techniques. From the several studies, it was also proved that biochar as an amendment has an effect of soil conditioner and improves soil fertility by affecting pH and CEC of the soil. While biochar is being applied to soils for the conditioning and fertilization purposes, this application can also be beneficial in

Fig 7 A simple charcoal production kiln

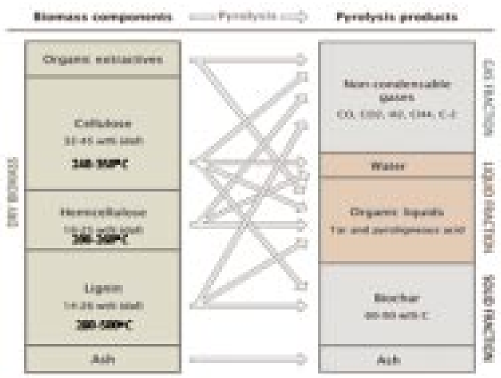

Fig 8 Generalized decomposition pattern of biomass from thermal decomposition in pyrolysis
(Source: Thomsen *et al*., 2011)

reducing of toxic components. Studies have shown that biochar is also capable of absorbing metals such as lead, and organics that contaminate soils which harm people, plants and animals. Biochar comes with the appeal of being a low cost and low-environmental-impact strategy for remediation of environmental pollutants and climate change mitigation.

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Carbon Credit

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Our earth is undoubtedly warming. This warming is largely the result of emissions of carbon dioxide and other greenhouse gases (GHGs) from human activities including industrial processes, fossil fuel combustion, and changes in land use, such as deforestation. Global warming has led to season shifting, changing landscapes, rising sea levels, increased risk of drought and floods, stronger storms, increase in heat related illness and diseases all over the world. Since the inception of Kyoto protocol in the year 1997, countries all over the world have become more concerned about 'Global Warming'.

The Kyoto Protocol is an agreement made under the United Nations Framework Convention on Climate Change (UNFCCC), which is an international environmental treaty with the goal of achieving "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The treaty was negotiated in Kyoto, Japan in December 1997, opened for signature on March 16, 1998, and closed on March 15, 1999. The agreement came into force on February 16, 2005, under which the industrialised countries will reduce their collective emissions of greenhouse gases by 5.2% compared to the year 1990 (but it may be noted that, compared to the emission levels that would be expected by 2010 without the Protocol, this target represents a 29% cut). The aim is to lower overall emissions of six greenhouse gases - carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs (Hydrofluro carbon), and PFCs - calculated as an average over the five-year period of 2008-12. National targets range from 8% reductions for the European Union, 7% for the US, 6% for Japan, 0% for Russia, and permitted increase of 8% for Australia and 10% for Iceland.

The UNFCCC divided countries into two main groups: A total of 41 industrialized countries are currently listed in the Convention's Annex-I, including the relatively wealthy industrialized countries that were members of the organization for economic co-operation and development (OECD) in 1992, plus countries with economies in transition (EITs), including the Russian Federation, the Baltic states, and several Central and Eastern European states. The OECD members of Annex-I (not the EITs) are also listed in the Convention's Annex-II. There are currently 24 such Annex-II parties. All other countries not listed in the Convention's Annexes (about 145 developing countries) are known as non-Annex-I countries.

Annex I countries such as United States of America, United Kingdom, Japan, New Zealand, Canada, Australia, Austria, Spain, France, Germany etc. agreed to reduce their emissions (particularly carbon dioxide) to target levels below their 1990 emissions levels. If they cannot do so, they must buy emission credits from developing countries or invest in conservation. Countries like United States of America, United Kingdom, Japan, New Zealand, Canada, Australia, Austria, Spain etc. are also included in Annex-II.

Developing countries (non-Annex-I) such as India, Srilanka, Afghanistan, China, Brazil, Iran, Kenya, Kuwait, Malaysia, Pakistan, Phillippines, Saudi Arabia, Sigapore, South Africa, UAE etc. have no immediate restrictions under the UNFCCC.

Fig 1 Kyoto Protocol participation map 2010

(Green indicates countries that have ratified the treaty; dark green are Annex I and II countries that have ratified the treaty; grey is not yet decided; brown has no intention of ratifying)

Carbon credit

A carbon credit is a generic term for any tradable certificate or permit representing the right to emit one tonne of carbon dioxide or the mass of another greenhouse gas equivalent to one tonne of carbon dioxide. One carbon credit is equal to one metric tonne of carbon dioxide, or in some markets, carbon dioxide equivalent gases.

Definitions

The Collins English dictionary defines carbon credit as "*a certificate showing that a government or company has paid to have a certain amount of carbon dioxide removed from the environment*".

The Environment Protection Authority of Victoria defines carbon credit as a "*generic term to assign a value to a reduction or offset of greenhouse gas emissions... usually equivalent to one tonne of carbon dioxide equivalent (CO_2-e).*"

The Investopedia Inc investment dictionary defines a carbon credit as a "*permit that allows the holder to emit one ton of carbon dioxide*" which "*can be traded in the international market at their current market price*".

Kyoto protocol flexible mechanisms

The Kyoto Protocol provides for three mechanisms that enable countries or operators in developed countries to acquire greenhouse gas reduction credits. The flexibility mechanisms are international emissions trading (IET), the clean development mechanism (CDM), and the joint implementation (JI).

IET allows Annex I countries to "trade" their emissions termed as assigned amount units (AAUs), or "allowances" for short. For IET, the economic basis for providing this flexibility is that the marginal cost of emission abatement differs among countries. Trade could potentially allow the Annex I countries to meet their emission reduction commitments at a reduced cost. This is because trade allows emissions to be abated first in countries where the costs of abatement are lowest, thus increasing the efficiency of the Kyoto agreement.

The CDM and JI are called "project-based mechanisms," in which they generate emission reductions from projects. The difference between IET and the project-based mechanisms is that IET is based on the setting of a quantitative restriction of emissions, while the CDM and JI are based on the idea of "production of emission reductions". The CDM is designed to encourage production of emission reductions in non-Annex I countries, while JI encourages production of emission reductions in Annex I countries.

The production of emission reductions generated by the CDM and JI can be used by Annex B countries in meeting their emission reduction commitments. The emission reductions produced by the CDM and JI are both measured against a hypothetical baseline of emissions that would have occurred in the absence of a particular emission reduction project. The emission reductions produced by the CDM are called certified emission reductions (CERs); reductions produced by JI are called emission reduction units (ERUs). The reductions are called "credits" because they are emission reductions credited against a hypothetical baseline of emissions.

- Under joint implementation (JI), a developed country with relatively high costs of domestic greenhouse reduction would set up a project in another developed country.
- Under the clean development mechanism (CDM), a developed country can sponsor a greenhouse gas reduction project in a developing country where the cost of greenhouse gas reduction project activities is usually much lower, but the atmospheric effect is globally equivalent. The developed country would be given credits for

meeting its emission reduction targets, while the developing country would receive the capital investment and clean technology or beneficial change in land use.

- Under international emissions trading (IET), countries can trade in the international carbon credit market to cover their shortfall in assigned amount units (AAU). Countries with surplus units can sell them to countries that are exceeding their emission targets under Annex B of the Kyoto protocol.

These carbon projects can be created by a national government or by an operator within the country. In reality, most of the transactions are not performed by national governments directly, but by operators who have been set quotas by their country.

Emission trading

- Emissions trading (ET) is a mechanism that enables countries with legally binding emission targets to buy and sell emissions allowances among themselves.
- Each country has a certain number of emission allowances (amount of CO_2 it can emit) in line with its Kyoto reduction targets.
- The IET allows industrialized countries to trade their surplus credits on the international carbon credit market.
- Emissions trading transfers "assigned amount units" or AAUs.
- The buyer will then use the credits to meet their emissions targets.
- A global carbon market is estimated to be around $30 billion.
- Currently, future contracts in carbon credits are actively traded in the European exchanges (ECX).
- Many companies actively participate to manage the risks associated with trading in carbon credits.
- Participants include project enablers, public utilities, manufacturing entities, brokers, banks, and others.
- Buyers – Annexure I countries
- Suppliers – Non annexure I countries.

Intergovernmental emissions trading

The design of the European Union emissions trading scheme (EU-ETS) implicitly allows for trade of national Kyoto obligations to occur between participating countries. Other than the trading that occurs as part of the EU-ETS, no intergovernmental emissions trading had taken place. One of the environmental problems with IET is the large surplus of allowances that are available. Russia, Ukraine, and the new EU-12 member states (the Kyoto Parties Annex I Economies-in-Transition, abbreviated "EIT": Belarus, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russian Federation, Slovakia, Slovenia, and Ukraine) have a surplus of allowances, while many OECD countries have a deficit. Some of the EITs with a surplus regard it as potential compensation for the trauma of their economic restructuring. OECD countries with a deficit could meet their Kyoto commitments by buying allowances from transition countries with a surplus. Unless other commitments were made to reduce the total surplus in allowances, such trade would not actually result in emissions being reduced.

Green investment scheme

A green investment scheme (GIS) refers to a plan for achieving environmental benefits from trading 'hot air' under the Kyoto protocol. The green investment scheme (GIS), a mechanism in the framework of international emission trade (IET), is designed to achieve greater flexibility in reaching the targets of the Kyoto protocol while preserving environmental integrity of IET. Under the GIS, a party to the protocol expecting that the development of its economy will not exhaust its Kyoto quota, can sell the excess of its Kyoto quota units (AAUs) to another party. The proceeds from the AAU sales should be "greened", i.e., channelled to the development and implementation of the projects either acquiring the greenhouse gases emission reductions (hard greening) or building up the necessary framework for this process (soft greening).

Joint implementation (JI)

- Projects between industrialized nations to earn emission offsets.
- It is done because of geographical or cost implications.
- Emission reduction units (ERUs) created through joint implementation is treated in the same way as those from emissions trading.
- The formal crediting period for joint implementation (JI) was aligned with the first commitment period of the Kyoto Protocol, and did not start until January 2008. In November 2008, only 22 JI projects had been officially approved and registered. The total projected emission savings from JI by 2012 are about one tenth that of the CDM.
- Russia accounts for about two-thirds of these savings, with the remainder divided roughly equally between the Ukraine and the EU's new member states. Emission savings include cuts in methane, HFC, and N_2O emissions.

Clean development mechanism (CDM)

- CDM is supervised by the CDM executive board (CDM EB) and is under the guidance of the conference of the parties (COP/MOP) of the UNFCCC.
- Certified emission reductions (CERs) commonly known as carbon credits, where each unit is equivalent to the reduction of one metric tonne of CO_2.
- The value of one CER in Indian Rupees is about Rs. 1600/- (as in 2007).

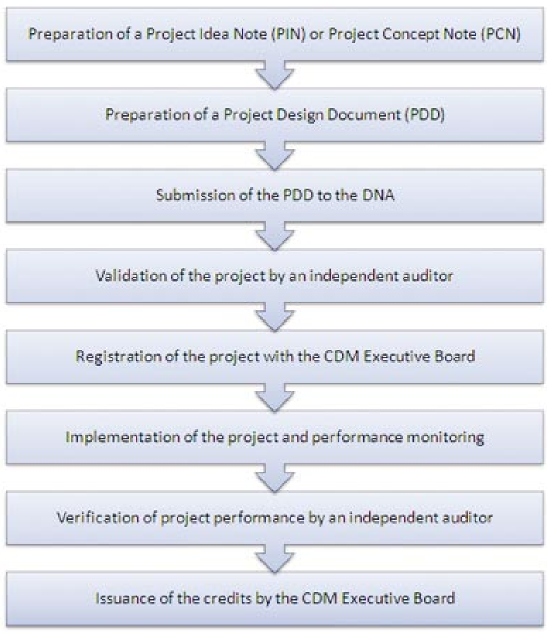
The clean development mechanism (CDM) is one of the "flexibility" mechanisms defined in the Kyoto protocol. It is defined in Article 12 of the Protocol, and is intended to meet two objectives:

1. to assist parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the United Nations framework convention on climate change (UNFCCC), which is to prevent dangerous climate change; and
2. to assist parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments on GHG emission caps. "Annex I" parties are those countries that are listed in Annex I of the treaty, and are the industrialized countries. Non-Annex I parties are developing countries.

Objective (2) is achieved by allowing the Annex I countries to meet part of their caps using "certified emission reductions" from CDM emission reduction projects in developing countries. This is subject to oversight to ensure that these emission reductions are real and additional.

The CDM allows industrialized countries to invest in emission reductions wherever it is cheapest globally. Between 2001, (the first year CDM project could be registered) and 2012, (the end of the Kyoto commitment period), the CDM is expected to produce some 1.5 billion tons of carbon dioxide equivalent (CO_2-e) in emission reductions. Most of these reductions are through renewable energy, energy efficiency, and fuel switching. Carbon capture and storage (CCS) was included in the CDM carbon offsetting scheme in December 2011.

CDM process



CDM project types

Energy efficiency projects

- Increasing building efficiency (concept of green building/LEED Rating), e.g., Technopolis IT building, ITC Sonar Hotel, Kolkata.
- Increasing commercial/industrial energy efficiency (Renovation and modernization of old power plants).
- Switching from more carbon intensive fuels to less carbon intensive fuels; and
- Re-powering, upgrading instrumentation, controls, and/or equipments.

Transport

- Improvements in vehicle fuel efficiency by the introduction of new technologies.
- Changes in vehicles and/or fuel type, for example, switch to electric cars or fuel cell vehicles (CNG/Bio fuels).
- Switch of transport mode, e.g., changing to less carbon intensive means of transport like trains (Metro in Delhi); and
- Reducing the frequency of the transport activity.

Methane recovery

- Animal waste methane recovery and utilization: Installing an anaerobic digester and utilizing methane to produce energy.
- Coal mine methane recovery: collection and utilization of fugitive methane from coal mining.
- Capture of biogas: landfill methane recovery and utilization.
- Capture and utilization of fugitive gas from gas pipelines.
- Methane collection and utilization from sewage/industrial waste treatment facilities.

Industrial process changes

Any industrial process change resulting in the reduction of any category greenhouse gas emissions.

Cogeneration

Use of waste heat from electric generation, such as exhaust from gas turbines, for industrial purposes or heating (e.g., Distillery-molasses/ bagasse).

Agricultural sector

- Energy efficiency improvements or switching to less carbon intensive energy sources for water pumps (irrigation).
- Methane reductions in rice cultivation.

- Reducing animal waste or using animal waste for energy generation.
- Any other changes in an agricultural practices resulting in reduction of any category of greenhouse gas emissions.

CDM projects to date

Since 2000, the CDM has allowed crediting of project-based emission reductions in developing countries. The EU ETS started in January 2005, and the following month saw the Kyoto protocol enter into force. The EU-ETS allowed firms to comply with their commitments by buying offset credits, and thus created a perceived value to projects. The Kyoto protocol set the CDM on a firm legal footing.

Companies and countries initially came forward with projects to reduce industrial gases, notably hydrofluorocarbon-23 (HFC-23) and nitrous oxide (N_2O). Some concerns were raised about these projects. HFC-23 is a potent greenhouse gas (GHG) and is a by-product of producing HCFC-22. The scale of the profits generated from CDM credits could have made it profitable to build whole new facilities just for the value of destroying the by-product. In response to this, the CDM executive board revised crediting to reduce the risk of perverse incentives.

Industrial gas projects, like those limiting HFC-23 emissions, are expected to contribute 20% of the CDM reduction in emissions to 2012. By the end of 2008, over 4,000 CDM projects had been submitted for validation, and of those, over 1,000 were registered at the CDM executive board, and were therefore entitled to generate CERs. The initial reductions of industrial gas projects included large contributions from South Korea and Brazil, followed by India and China.

As of 21st November 2011, 3583 projects have been registered by the CDM Executive Board as CDM projects. These projects reduce greenhouse gas emissions by an estimated 538 million ton CO_2 equivalent per year. There are about 5,600 projects yet to be certified. These projects would reduce CO_2 emissions by over 2.7 billion tons until the end of 2012. However, the previous adoption rate suggests that only a fraction of these projects will be certified. The current emissions of the EU-15 are about 4.2 billion ton CO_2 equivalent per year. The majority of CERs issued so far have been from HFC destruction projects. However, there are only a limited number of such project sites globally, of which most, if not all, have already been converted into projects. The fastest-growing project types are renewable energy and energy efficiency. By 2012, the largest potential for production of CERs are estimated in China (52% of total CERs) and India (16%). CERs produced in Latin America and the Caribbean make up 15% of the potential total, with Brazil as the largest producer in the region (7%).

Overview of carbon market

Carbon trading refers to a wide range of trading possibilities. In the classic scenario, it refers to a cap-and-trade system wherein, a cap is specified to an entity and if it abates lower than the cap it becomes a net seller, and if its emissions exceed the cap then it becomes a net buyer. Under the Kyoto protocol, the Annex-I countries can participate in such emissions trading during the Kyoto commitment period. Besides this, there are other forms of carbon trading with the carbon permits originating from project based emission mitigation activities such as clean development mechanism (CDM). Similarly, carbon permits are also traded among entities based on voluntary commitments. The Kyoto protocol (in its article 17) allows Annex-I countries to participate in emissions trading for the purpose of fulfilling their commitments, provided trading is supplemental to domestic action. Thus, the Annex-I countries that are unable to meet their Kyoto targets can purchase carbon credits from other countries in the form of: (a) assigned amount units, (b) certified emissions credits, (c) emission reduction units, and (d) removal units on the basis of land use, land-use change and forestry activities.

Broadly carbon market can be divided into

a. regulated markets
b. voluntary markets.

These two markets can be viewed in two different ways:

Demand side: When viewed from the demand side of carbon permits, 'regulated market' refers to countries and companies that have a mandatory cap on the amount of CO_2 they can produce. 'Voluntary market' on the other hand refers to entities taking action to meet other goals such as corporate social responsibility, brand building, product differentiation, and even moral obligations.

Supply side: When viewed from the supply side of carbon permits, 'regulated market' refers to carbon instruments that have been certified as compliant with a mandatory system (e.g., CDM), whereas, 'voluntary market' refers to carbon instruments that have been developed outside any mandatory system (e.g., voluntary carbon standard).

AAUs – Assigned amount units, are issued to countries with emission cap under Kyoto Protocol (i.e., Annex-I countries);

EUAs – European Union allowances, the allowances in use under EU-ETS. Both AAUs and EUAs represent one metric ton of carbon dioxide equivalent.

CERs – Certified emission reductions, a unit of GHG emission reductions issued pursuant to the clean development mechanism of the Kyoto protocol.

ERUs – Emission reduction units, a unit of GHG emission reductions issued pursuant to Joint Implementation of the Kyoto protocol. Both CERs and ERUs represent one metric ton of carbon dioxide equivalent.

CFIs – Carbon finance instruments are instruments used for compliance with the Chicago climate exchange commitments.

CCBA – Climate, community and biodiversity alliance

VCS – Voluntary carbon standard

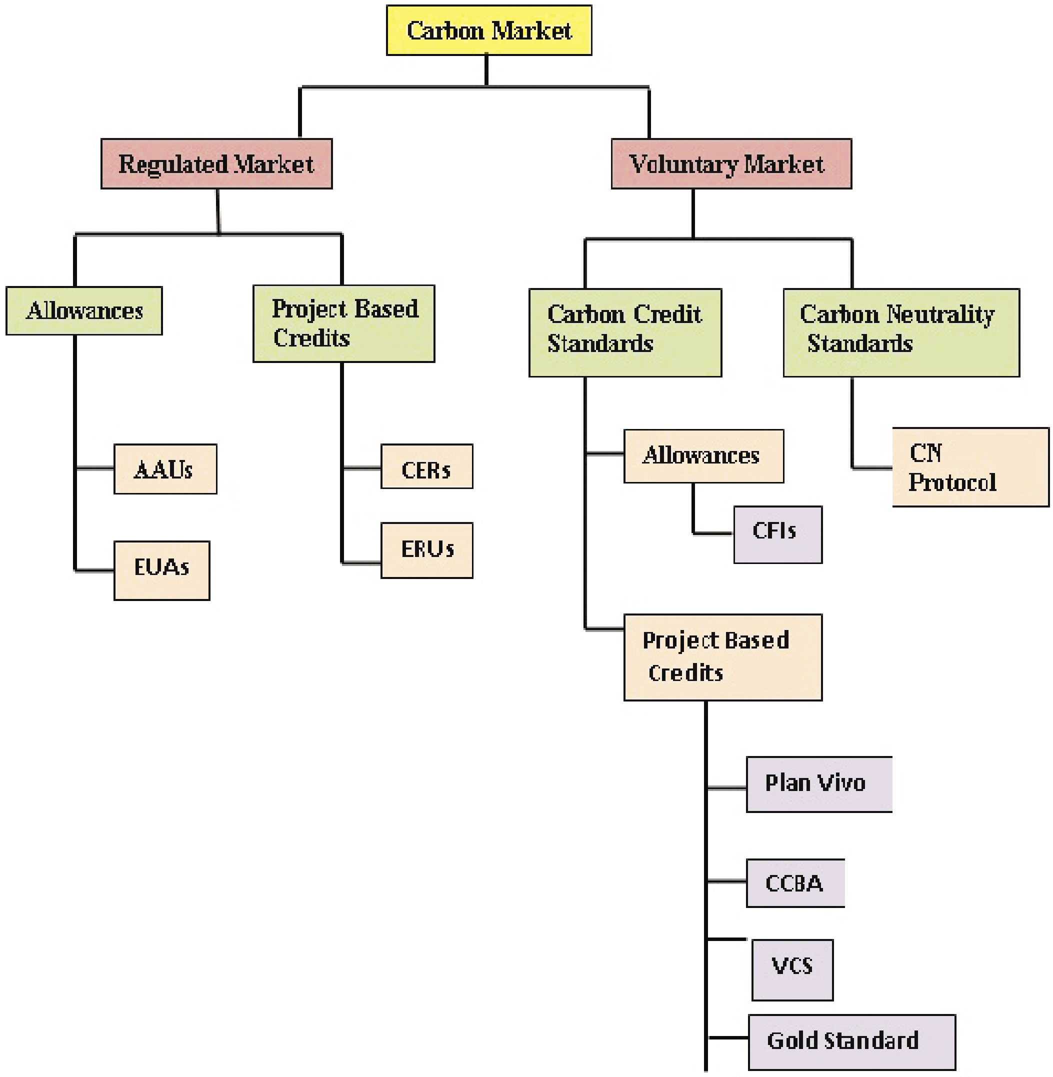


Fig 2 General structure of Carbon Market

VER – Verified emission reductions

CN Protocol – Carbon neutral protocol.

How buying carbon credits can reduce emissions

- By giving monetary value to the cost of polluting the air.
- Offering solutions for regulatory, economic, investment and environmental needs.
- Carbon finance can be leveraged to develop projects that create biodiversity assets, support livelihoods through rural development thus reducing poverty and increasing employment.
- Provide incentive to land owners for carbon sequestration thereby stabilizing climatic changes and preserve forest ecosystems.
- Emissions become an internal cost of doing business and are visible on the balance sheet alongside raw materials and other liabilities or assets.

Indian scenario

India comes under the third category of signatories to UNFCCC. India signed and ratified the protocol in August, 2002 and has no immediate restrictions under the UNFCCC. This serves three purposes:

a) Avoids restrictions on growth because pollution is strongly linked to industrial growth, and developing economies can potentially grow very fast.

b) It means that they cannot sell emission credits to industrialized nations to permit those nations to over-pollute.

c) They get money and technologies from the developed countries.

India has emerged as a world leader in reduction of greenhouse gases by adopting clean development mechanisms (CDMs) in the past few years. According to report on National action plan for operationalising clean development mechanism (CDM) by Planning Commission, Govt. of India, the total CO_2-equivalent emissions in 1990 were 10,01,352 Gg (Gigagrams), which was approximately 3% of global emissions. If India can capture a 10% share of the global CDM market, annual CER revenues to the country could range from US$ 10 million to 300 million (assuming that CDM is used to meet 10-50% of the global demand for GHG emission reduction of roughly 1 billion tonnes CO_2, and prices range from US$ 3.5-5.5 per tonne of CO_2). As the deadline for meeting the Kyoto protocol targets draws nearer, prices can be expected to rise, as countries/companies save carbon credits to meet strict targets in the future. India is well ahead in establishing a full-fledged system in operationalizing CDM, through the designated national authority (DNA). Other than Industries and transportation, the major sources of GHG emission in India are: paddy fields, enteric fermentation from cattle and buffaloes and municipal solid waste of the these three sources, the emissions from the paddy fields can be reduced through special irrigation strategy and appropriate choice of cultivars; whereas enteric fermentation emission can be reduced through proper feed management. In recent days, the third source of emission i.e., municipal solid waste dumping grounds are emerging as a potential CDM activity despite being provided least attention till date.

Indian companies: taking advantage

- **Gujarat fluro chemicals** is amongst 1st companies worldwide to get its carbon emission reduction project certified. It is set to reap rewards from the sale of CER credits from this year itself.
- **Tata steel** is believed to have signed a MoU with the Japanese government agency "NEDO" for sale of credits accruing to it from carbon reduction following the implementation of an over Rs 250 crore modernization and up-gradation project.
- **NTPC** and several state electricity boards have also applied for carbon credit benefits. Most of them are replacing coal-based technologies with more environment-friendly processes.

Of the 15 projects approved by the UNFCCC so far, 4 are Indian. These 4 are: Gujarat fluro chemicals, the Clarion power project in Rajasthan, Kalpataru power transmission Ltd, The Dehar power project in Himachal Pradesh.

The country accounted for 283 CDM projects out of the 819 registered by the CDM executive board, the MoEF, the World Bank and the international emissions trading association.

- India has generated approximately 30 million carbon credits and approximately 140 million in run, the second highest transacted volume in the world.
- India's carbon market is growing faster than even information technology, bio technology and BPO sectors as 850 projects with a huge investment of Rs 650,000 million are in pipeline.
- As per the Prime Minister's council on climate change, the revenue from 200 projects is estimated at Rs. 97 billion by 2012.
- India has been able to register approximately 350 projects spread across various sectors with major dominance of renewable energy, energy efficiency and biomass energy projects.
- Carbon, like any other commodity, has begun to be traded on India's multi commodity exchange and has become first exchange in Asia to trade carbon credits.

Conclusion

Great opportunity is awaiting India in carbon trading. In the new regime, the country could emerge as one of the largest beneficiaries accounting for 25 per cent of the total world carbon trade, says a recent World Bank report. The countries like USA, Germany, Japan and China are likely to be the biggest buyers of carbon credits which are beneficial for India to a great extent. The Indian market is extremely receptive to clean development mechanism (CDM). Having cornered more than half of the global tradable certified emission reduction (CERs), India's dominance in carbon trading under the Clean Development Mechanism (CDM) of the UN framework convention on climate change (UNFCCC) is beginning to influence business dynamics in the country. India Inc pocketed Rs 1,500 crores in the year 2005 just by selling carbon credits to developed-country clients. Various projects would create up to 306 million tradable CERs. Analysts claim, if more companies absorb clean technologies, total CERs with India could touch 500 million. Hence, MSW dumping grounds can be a huge prospect for CDM projects in India. These types of projects would not only be beneficial for the Government bodies and stakeholders but also for general public.

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Sustainable Agricultural Production through Amelioration of Site-specific Soil Physical Constraints

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Introduction

Sustainable agriculture aims at meeting the needs of present generation without endangering the resource base of the future generation. Unfortunately, unsustainable productivity, declining yield, environmental pollution, decreasing soil organic matter content, decreasing factor productivity under high intensity agriculture in the post green revolution era has been a matter of great concern in the recent days. So, to sustain the productivity at higher level is the key issue in Indian agriculture to meet the increasing demands of food and fiber for the growing population. Maintaining soil health is indispensable for sustaining the agricultural productivity at higher level. The term soil health and soil quality are often used interchangeably in the scientific literature. Soil quality is defined as the capacity of soil to function within the ecosystem and landuse boundaries, to sustain biological productivity, maintain the environmental quality and promote plant, animal and human health (Doran and Parkin, 1994). Soil quality includes three groups of mutually interactive attributes i.e., soil physical, chemical and biological quality, which must be restored at its optimum to sustain productivity at higher levels in the long run. Thus, it is high time to appreciate the fact that unless the soil physical environment is maintained at its optimum level the genetic yield potential of a crop cannot be realized. Soil physical constraints refer to a situation where the soil physical environment is not at optimum condition to produce higher yields of crops.

Distribution of area affected by various soil physical constraints in India

It is estimated that out of the 328 m ha of the total geographical area in India, 173.65 m ha are degraded, producing less than 20% of its potential capacity and out of this 89.52 m ha suffers from one or the other form of physical constraints (Table 1). Shallow depth, soil hardening, slow permeability, sub-surface compacted layer, surface crusting, temporary water logging etc. are the major physical constraints of Indian soils (Painuli and Yadav, 1998). The nature and extent of physical constraints are however, not static. Mechanization of farm operations, frequent tillage in intensive cropping systems, unscientific and indiscriminate use

Table 1 Distribution of area affected by various physical constraints in India

Physical constraints	Area (m ha)	Main states affected
Shallow depth	26.40	Andhra Pradesh, Maharashtra, West Bengal, Kerala and Gujarat
Soil hardening	21.57	Andhra Pradesh, Maharashtra and Bihar
High permeability	13.75	Rajasthan, West Bengal, Gujarat, Punjab and Tamil Nadu
Subsurface hard pan	11.31	Maharashtra, Punjab, Bihar, Rajasthan, West Bengal and Tamil Nadu
Surface crusting	10.25	Haryana, Punjab, West Bengal, Orissa and Gujarat
Temporary water logging	6.24	Madhya Pradesh, Maharashtra, Punjab, Gujarat, Kerala and Orissa

of inputs and decline in soil organic matter are adding new areas with new problems to the existing area. The current scenario calls for appreciating the fact that once degraded, it is difficult if not impossible to restore the soil to its good physical condition, and also that unlike the solutions for fertility problems, corrective measures for physical problems is not available easily and cheaply. Persistent efforts are warranted to arrest further aggravation of soil degradation, to alleviate soil physical constraints and also to understand the respective causal processes for the holistic, safe and resilient agricultural production system. Therefore, our sincere efforts must be to improve and maintain soil physical environment at its optimum condition with minimal risks to the environment.

Recognizing the importance of soil physical environment, the Indian Council of Agricultural Research, New Delhi started an All India Coordinated Research Project (AICRP) on "Studies on measurement and improvement of soil structure" in 1967. This project has undergone many transformations during the course of time and by the time it was phased out in 1999 its title was modified to AICRP on "Soil Physical constraints and their amelioration for sustainable crop production". There were 13 coordinated centers of this project spread across the country *viz*., New Delhi, Hisar, Jabalpur, Coimbatore, Hyderabad, Sobur, Jobner, Kharagpur, Ludhiana, Parbhani, Palampur, Bhubaneshwar and Thiruvananthapuram to address site specific soil physical problems. Significant achievements have been made in this project to identify and alleviate the site-specific soil physical constraints and improve crop yield (Progress Report, 1997-1999, AICRP on Soil Physical Constraints). Identification and delineation of soil physical constraints in this project was done through study of benchmark soil profiles for physical characteristics such as texture, aggregation, hydraulic conductivity, bulk density, infiltration rate, pore size distribution and water retention characteristics of soil.

Technologies for alleviation of soil physical constraints

Management of highly permeable soils

Light textured laterite and fluffy soils show high permeability, which causes losses of water and nutrients. Three technologies have been developed for management of highly permeable soils *viz*., compaction, clay addition and compaction plus clay addition (Painuli and Yadav, 1998).

i. **Compaction:** It involves repeated passes of a roller of sufficient weight drawn by animal or tractor at optimum soil moisture content (Proctor moisture) to attain the desired level of compaction. The level of compaction is specific for specific soil-climate crop combination. Most spectacular results of this technology were observed in lateritic soils of West Bengal and coastal sandy soils (fluffy soil) of Tamil Nadu. Yield increase in the range of 20-45% was obtained for the first crop and significant residual effects were possible up to third crop after compaction (Table 2).

ii. **Clay addition technology:** Addition of clay @ 2% in red sandy loam of Andhra Pradesh increased crop yield by more than 10 per cent. Continuous addition at the same rate is recommended for 2-3 years. This technology resulted in increase in sorghum (16%) and tomato (11%) yield at Hyderabad (Table 2). This was possible due to formation of stable aggregates and increase in water and nutrient retention due to clay. This technology is viable where fine textured soil is available either from ponds or nearby fields.

Table 2 Field evaluation of technologies developed for highly permeable soils

Technology	Soil type (location)	No. of years	Crop	Increase in yield (%)
Compaction	Sandy (Coimbatore)	1	Groundnut	20.0
	Loamy sand (Hisar)	4	Pearlmillet	13.3
	Loamy sand (Delhi)	4	Wheat	4.6
Clay mixing	Red sandy loam	3	Sorghum	16.0
	(Hyderabad)	3	Tomato	10.8
Clay mixing + Compaction	Sandy to Sandy loam	17	Wheat	29.0
	(Jobner)	17	Pearlmillet	37.0

iii. **Clay addition and compaction technology:** The desired effect of compaction technology was not obtained in desert soils without addition of clay, as these soils are very poor in finer fractions. This technology involves compaction after addition of 2% clay. The result in terms of water and nutrient retention and yield sustainability was so phenomenal in desert soils that this is popularly referred as “Desert Technology”. This technology has resulted in significant increase in yield of wheat

(29%) and pearlmillet (37%) (Table 2). A low cost roller, known as Jobner reinforced iron concrete roller (JRIC roller), was designed and fabricated at Jobner for implementing this technology.

Technologies for soils with subsurface mechanical impedance

Subsurface mechanical impedance restricts root growth and movement of air, water and nutrients, which affect crop yield. Three technologies have been developed to alleviate this problem *viz*., chisel technology, chisel plus amendment technology and ridge technology (Painuli and Yadav, 1998).

i. **Chisel technology:** It has been observed that deep tillage/chiseling breaks the subsurface compacted layer or hardpan and thereby facilitates vertical and horizontal growth of roots. Depending upon soil and crop requirement, chiseling up to 30-50 cm depth at 50-60 cm intervals has been recommended. Though the residual effect of chiseling has been significant upto seventh successive crop in red soils, the effect diminished more rapidly in light textured soils. Hence, chiseling in every kharif season in light textured soil and once in 2-3 years in red soils is useful. A low cost chisel plough for this purpose has been developed and fabricated at Coimbatore. Chiseling to a depth of 35 cm at an interval of 50 cm resulted in significant increase in yield of soybean and pigeonpea in vertisols of Bhopal (Ghosh *et al*., 2006) (Table 3) and that of maize in red soil of Coimbatore and cotton in sandy loam soil of Hisar (Table 4).

Table 3 Effect of sub-soiling on soybean equivalent yield of soybean and pigeonpea as sole and intercrop

Tillage	Soybean equivalent yield of different cropping systems (kg ha^{-1})			
	Soybean	Pigeonpea	Soybean/Pigeonpea	Mean
Year 2001				
Conventional tillage	1235	1752	1823	1638
Conventional tillage + Deep tillage- Alternate year	1400	1788	2012	1715
Conventional tillage + Deep tillage- Every year	1472	2036	2126	1862
LSD (0.05) Tillage:155; Cropping system: 225; Tillage x Cropping system: 160				
Year 2002				
Conventional tillage	1029	1450	1590	1356
Conventional tillage + Deep tillage- Alternate year	1200	1620	1860	1560
Conventional tillage + Deep tillage- Every year	1290	1755	1990	1678
LSD (0.05) Tillage:120; Cropping system: 150; Tillage x Cropping system: 125				

ii. **Chisel plus amendments technology:** Subsurface compacted layer in black soils broken by chiseling rebuild compaction due to rapid swelling upon wetting of montmorillonitic clays. Addition of amendments like gypsum @ 5 t ha^{-1} or FYM @ 25 t ha^{-1} reduced the rate of compaction. At Nizamabad (Andhra Pradesh) amendments plus chiseling resulted in 12 per cent increase in sugarcane yield over chiseling alone and 25 per cent over conventional tillage (Table 4).

Table 4 Field evaluation of technologies developed for soils having subsurface mechanical impedence

Technology	Soil type (location)	No. of years	Crop	Increase in yield (%)
Chisel technology (45 cm depth, 50 cm interval)	Red soil (Coimbatore)	1	Maize (I[st] crop) Maize (II[nd] crop)	55.7 28.2
Chisel technology (45 cm depth, 50 cm interval)	Sandy loam soil (Hisar)	-	Cotton	17.0
Chisel + amendment (gypsum @ 5 t ha^{-1} or FYM @ 25 t ha^{-1})	Black soil (Nizamabad)	1	Sugarcane	25.4
	Sandy loam soil (Hisar)	17	Mustard Pearlmillet	33.0 37.0

iii. **Ridge technology:** By construction of ridges, rooting volume above the compacted layer increases and thus the crop yield increases. The yield of mustard grown on ridges increased by 33 per cent and that of pearl millet increased by 37 per cent over flat cultivation at Hisar.

Technology for hardening soils

Rapid and irreversible hardening of red *'chalka'* soils upon drying is a major constraint in production of groundnut and root crops. Addition of slow decomposing residues like paddy husk, coir pith etc. followed by appropriate tillage has proved very useful (Painuli and Yadav, 1998). The efficiency of various amendments at different rates were evaluated and their efficiency was found in the order FYM @ 10 t ha^{-1} > coir pith @ 20 t ha^{-1} > powdered groundnut shell @ 5 t ha^{-1} > gypsum @ 4 t ha^{-1} > paddy husk @ 5 t ha^{-1} (Nagarajarao and Gupta, 1996). Application of paddy husk @ 5 t ha^{-1} resulted in increase in yield of sorghum and castor by 14-23% (Table 5).

Technology for crusting soils

Soil aggregates are easily dispersed in soils of low organic matter under the impact of rain drops, thus forcing a thin layer of dispersed soil (clay) on the soil surface which on drying forms crust. This reduces the exchange of gases between soil and atmosphere and

Table 5 Technology developed for hardening red soils of Hyderabad

Technology	No. of trials	Crop	Increase in yield (%)
Paddy husk @ 5 t ha^{-1}	6	Sorghum (Ist crop)	18.0
	1	Castor (IInd crop)	23.0
	1	Sorghum (IInd crop)	13.6

also injures the tips of emerging seedlings, resulting in drastic reduction in plant population. A technology called "Seed line mulch technology" has been developed to alleviate this problem (Nagarajarao and Gupta, 1996). This involves application of FYM @ 3 t ha^{-1} or chopped wheat straw (bhusa) on the seeded rows immediately after sowing. This prevented the disintegration of aggregates and dispersion of soil and maintained 3% higher soil water in the crusted soil in the upper 5 cm layer during seedling emergence. This technology significantly improved the seedling emergence and yield of pearl millet, sorghum, cotton and jute over crusted soil (Table 6).

Table 6 Effect of seed line mulch technology on seedling emergence and crop yield

Treatment	Seedling emergence (%)		Yield (t ha^{-1})	
	Pearlmillet	Cotton	Pearlmillet	Cotton
Crusted soil	59	3.6	2.23	0.35
Mechanical breaking	69	32.8	3.05	1.45
FYM @ 3 t ha^{-1} on seed lines	73	20.2	3.35	1.49
Wheat straw @ 2 t ha^{-1} on seed lines	80	28.9	3.39	1.53
Uncrusted	79	35.5	3.25	1.47
LSD (5%)	9	7.6	0.83	0.33

Technology for shallow soils

Insufficient soil volume limits root growth and supply of water and nutrients to the crop in required amount. Construction of 10 cm high ridge on shallow soils of depth ranging from 15 to 35 cm was found beneficial for root growth. As a consequence, maize yield increased by 50 and 41 per cent in 15 and 35 cm deep soils, respectively (Painuli and Yadav, 1998). Addition of clay or paddy husk further improved the physical condition and crop growth. Similar responses were found for sorghum and gram and sunflower. In the sloppy red soils of Andhra Pradesh, farmers face the twin problems of shallow depth and erosion. Formation of ridges and furrow on contours along with *khus* (vertiveria) barrier at a vertical interval of 1 m reduced runoff and soil loss by 88 and 92 per cent, respectively. This also helped in maximum moisture retention during crop growth and higher crop yields (Table 7).

Table 7 Technology developed for shallow soils of Hyderabad

Technology	Topography	Crop	Increase in yield (%)
Ridge technology (10 cm high along contour)	Flat	Sorghum	10.3
		Castor (IInd crop)	27.9
		Okra	10.5
Ridge technology + *khus* barrier	Slopping	Castor	35.0

Technologies for slowly permeable black soils (temporary water logging)

Various tillage and land form treatments *viz*., ridges and furrow, broad bed and furrow and raised and sunken beds of different widths were found effective in black soils of low rainfall (Parbhani) and high rainfall (Jabalpur) areas to avoid waterlogging during rainy season (Table 8) (Painuli and Yadav, 1998). These practices have been found effective to various extents depending on topography, crop and rainfall. The raised and sunken bed technology involves construction of raised bed alternating with sunken bed. This technology is most promising on leveled land. The width of raised bed and sunken bed varies with the amount of rainfall. At Jabalpur with average annual rainfall of 1330 mm, a combination of 9 m wide raised bed (30-35 cm) and 6 m wide sunken bed have been found very effective whereas equal widths were most effective at Parbhani having average annual rainfall of 830 mm. The crops susceptible to waterlogging *e.g*., soybean, chick pea, sorghum were grown on raised beds and those resistant to water logging like rice were grown on sunken beds. Thus, crops requiring contrasting physical environment *i.e*., aerobic and anaerobic, get it as per their requirement. The yields of soybean and chickpea on raised bed increased by 86 and 36 per cent, respectively over flat bed. Another important benefit was that double cropping during the same year was possible on black soils, which otherwise used to remain water logged and thus fallow in rainy season in high rainfall areas. In vertisols of Bhopal, practicing broad bed and furrow method could increase the seed yield of soybean and reduced runoff, soil loss and nitrogen loss compared to flat cultivation method (Table 9).

Table 8 Technology developed for slowly permeable black soils

Technology	Location	Crop	Increase in yield (%)
Ridge and furrow	Jabalpur	Sorghum	27.2
		Soybean	14.9
	Parbhani	Sorghum	17.3
Broad bed and furrow	Parbhani	Sorghum	25.2
		Green gram	18.3
Raised bed and Sunken bed (9 m-6 m)	Jabalpur	Soybean	112.4
		Paddy	136.4
Raised bed and Sunken bed (1.5 m-3 m)	Parbhani	Paddy	38.4
		Sorghum	55.2

Table 9 Effect of landform treatment on soybean yield, runoff, soil and nutrient loss in a deep vertisols at Bhopal

Parameters	Flat on grade(FOG)	Broad bed and furrow (BBF)	Change in BBF compared to FOG (%)
Soybean seed yield (kg/ha)	1174	1214	+3.4
Runoff (mm)	125.8	80.07	-36.4
Soil loss (kg/ha)	2087.2	1003.2	-51.9
N loss (kg/ha)	34.89	22.09	-36.7

Economic appraisal of the technologies

Economic aspect is the prime concern for adoption of any technology from farmers' point of view. All the technologies discussed above are economically viable as the benefit: cost ratio of 1.13 to 5.28 was achieved in all these cases though these technologies require considerable initial investment by the farmers (Table 10). Further, the economic analyses revealed that the investment made by the farmer could be recovered in the first crop and first year itself. The economic benefit of these technologies lasted for more than one year. Besides economic benefit, these technologies also resulted in conserving soil and water and enhancing input use efficiency and improving soil quality.

Table 10 Economic appraisal of the technologies

Technology	Crop	Location	B:C ratio
Compaction	Wheat	Delhi	3.13
	Maize	Delhi	2.19
	Rice-wheat	Kharagpur	1.26
Clay mixing (2% Clay)	Sorghum	Hyderabad	1.37
Clay mixing (2% Clay) + Compaction	Pearlmillet	Jobner	5.28
Chiseling	Sorghum	Hyderabad	1.37
	Sorghum	Coimbatore	1.13
	Tapioca	Coimbatore	2.43
	Groundnut	Coimbatore	3.20
	Maize	Coimbatore	2.67
Raised and sunken bed	Soybean	Jabalpur	3.94
	Chickpea	Jabalpur	2.35
	Paddy	Jabalpur	1.57
Ridge + *Khus* barrier	Castor	Hyderabad	2.00
Residue incorporation	Sorghum-Castor	Hyderabad	3.09

Adoption of these economically viable eco-friendly technologies require concerted efforts by various state agencies, extension workers and NGOs and should be considered for managing natural resource of soil for sustaining productivity at higher level. Further, research endeavor is required to carry out the impact assessment of these technologies, identify and delineate any other soil physical constraints through comprehensive indices using minimum data sets and development and refinement of eco-friendly technologies in a farmers' participatory approach to alleviate these constraints.

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