Multifunctional agroforestry systems in India

Deep Narayan Pandey

Center for International Forestry Research (CIFOR), Bogor, Indonesia
Present address: Forestry Training Institute, Jawaharlal Nehru Marg, Jaipur 302 015, India

Land-use options that increase resilience and reduce vulnerability of contemporary societies are fundamental to livelihood improvement and adaptation to environmental change. Agroforestry as a traditional land-use adaptation may potentially support livelihood improvement through simultaneous production of food, fodder and firewood as well as mitigation of the impact of climate change. Drawing on the representative literature, here, I critically review the contribution of agroforestry systems in India to: (i) biodiversity conservation; (ii) yield of goods and services to society; (iii) augmentation of the carbon storage in agroecosystems; (iv) enhancing the fertility of the soils, and (v) providing social and economic well-being to people. Agroforestry systems in India contribute variously to ecological, social and economic functions, but they are only complementary – and not as an alternative – to natural ecosystems. To promote well-being of the society, management of multifunctional agroforestry needs to be strengthened by innovations in domestication of useful species and crafting market regimes for the products derived from agroforestry and ethnoforestry systems. Future research is required to eliminate many of the uncertainties that remain, and also carefully test the main functions attributed to agroforestry against alternative land-use options in order to know unequivocally as to what extent agroforestry served these purposes.

Keywords: Biodiversity conservation, biological pest control, carbon sequestration, ethnoforestry, food security.

LAND-use options that increase livelihood security and reduce vulnerability to climate and environmental change are necessary. Traditional resource management adaptations such as agroforestry systems, may potentially provide options for improvement in livelihoods through simultaneous production of food, fodder and firewood as well as mitigation of the impact of climate change.

A livelihood is a means of deriving a just and dignified living by the society, family and individuals. It comprises of the assets available to households (human, financial, physical, natural and social capital), the activities, and the access to these (mediated by institutions and social relations) that together determine the living gained by the society, households or individuals[1,2]. A livelihood can be urban or rural depending upon the context in which families derive their living. A livelihood can be sustainable when it can cope with and recover from stresses and shocks, and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural capital[3]. Livelihood improvement through natural resource management seeks to understand individual or household strategies through which long-term progress is made towards a better quality of life[4].

Livelihood improvement is not just about the positive change towards better quality of life and human well-being, but it takes into account the local and global change which determines the livelihood[5]. The adverse impact of climate change may be more severely felt by the poor, who are more vulnerable than the rich. Appropriate policy responses combining agroecosystems as key assets can strengthen adaptation and help build the resilience of communities and households to local and global change[6]. Steps to promote the mainstreaming of adaptation into livelihood improvement may potentially deliver better results when combined with adaptive management of natural resources and agroecosystems.

There is a need for intensified conservation efforts as well as growing products and generating services in agroecosystems[7]. Tree-growing in combination with agriculture (agroforestry systems) as well as numerous vegetation management regimes in cultural landscape (ethnoforestry systems), including individual farms, watersheds and regional landscape can be integrated to take advantage of the services provided by adjacent natural, semi-natural or restored ecosystems.

Increasing the livelihood security and reducing the vulnerability call for societal adaptation[8]. Such adaptations are possible when combined with traditional resource management systems. Agroforestry as a local adaptation, therefore, is a promising area of interest. This review examines the multifunctional agroforestry systems in India as a potential option for livelihood improvement, climate change mitigation, biodiversity conservation in agroecosystems as well as yield of goods and services to the society. Synthesis of the available literature also helps identify the remaining uncertainties and thus the future directions for research.

Trees in agroecosystems and cultural landscapes in India

Trees have a special role in the ethos of the people of India. There are several sacred trees and sacred groves valued

e-mail: d.pandey@livelihoods.in

by the people. India also has a long historical tradition of tree-growing on farms and around homes. Such traditions and indigenous ethics had and continue to have an impact and implications for tree-growing and ecological, economic and social well-being of the people. Sacred elements and traditional practices in cultural landscape of India also have a substantial livelihood and conservation value[9].

Agroforestry systems in India include trees in farms, community forestry and a variety of local forest management and ethnoforestry practices[10]. A wider definition of agroforestry encompasses a variety of practices, including trees on farm boundaries, trees grown in close association with village rainwater collection ponds, crop-fallow rotations, and a variety of agroforests, silvopastoral systems, and trees within settlements. These systems have been presented as a solution to rising fuelwood prices in India resulting from increase in demand and decrease in supply of fuelwood due to forest degradation[11].

Overall, India is estimated to have between 14,224 million[12] and 24,602 million[13] trees outside forests, spread over an equivalent area of 17 million ha[14], supplying 49% of the 201 million tonnes of fuelwood and 48% of the 64 million m^3 of timber consumed annually by the country[15].

Agroforestry systems as carbon sinks

Land-management actions that enhance the uptake of CO_2 or reduce its emissions have the potential to remove a significant amount of CO_2 from the atmosphere if the trees are harvested, accompanied by regeneration of the area, and sequestered carbon is locked through non-destructive (non-CO_2 emitting) use of such wood.

Carbon management through afforestation and reforestation in degraded natural forests is an useful option, but agroforestry is attractive because[16]: (i) it sequesters carbon in vegetation and possibly in soils depending on the pre-conversion soil C; (ii) the more intensive use of land for agricultural production reduces the need for slash-and-burn or shifting cultivation, which contributes to deforestation; (iii) the wood products produced under agroforestry serve as a substitute for similar products unsustainably harvested from the natural forest and (iv) to the extent that agroforestry increases the income of farmers, it reduces the incentive for further extraction from the natural forest for income augmentation.

Evidence is now emerging that agroforestry systems are promising management practices to increase aboveground and soil C stocks to mitigate greenhouse gas emissions. The C sequestration potential of tropical agroforestry systems in recent studies is estimated between 12 and 228 Mg ha^{-1}, with a median value of 95 Mg ha^{-1}. Therefore, based on the global estimates of the area suitable for the agroforestry (585–1215 $\times$ 10^6 ha), 1.1–2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years[17].

In India, average sequestration potential in agroforestry has been estimated to be 25 tC per ha over 96 million ha[18], but there is a considerable variation in different regions depending upon the biomass production (Table 1). However, compared to degraded systems, agroforestry may hold more carbon. For example, the above-ground biomass accumulation in a Central Himalayan agroforestry system has been found to be 3.9 t ha^{-1} yr^{-1} compared to 1.1 t ha^{-1} yr^{-1} at the degraded forestland[19].

A major uncertainty, and therefore an issue for future research, is that these estimates are mostly derived through biomass productivity and often do not take into account carbon sequestration in the soil[20]. In order to exploit the mostly unrealized potential of carbon sequestration through agroforestry, in both subsistence and commercial enterprises innovative policies, based on rigorous research results, are required.

Enhancing soil fertility and water use efficiency

Ecological intensification of cropping systems in fluctuating environments often depends on reducing the reliance on subsistence cereal production, integration with livestock enterprises, greater crop diversification, and agroforestry systems that provide higher economic value and also foster soil conservation. Maintenance and enhancement of soil fertility is vital for global food security and environmental sustainability. Although currently India is self-sufficient in terms of food production, for a population expected to rise further, the country will need to enhance both food production as well as tree biomass. The next green revolution and concurrent environmental protection will have to double the food production[21]. Maintaining and enhancing the soil fertility of farmlands to grow foodgrains as well as tree biomass can help meet the demand in future. Ecologically sound agroforestry systems such as intercropping and mixed arable-livestock systems can increase the sustainability of agricultural production while reducing on-site and off-site consequences and lead to sustainable agriculture[22].

In regions where the green revolution has not been able make a dent due to lack of soil fertility, agroforestry may hold promise. A useful path, complementary to chemical fertilizers, to enhance soil fertility is through agroforestry. Alternate land-use systems such as agroforestry, agro-horticultural, agro-pastoral and agro-silvipasture are more effective for soil organic matter restoration[23]. Soil fertility can also be regained in shifting cultivation areas with suitable species. For instance, a field experiment to study N_2 fixation efficiency suggests that planting of stem-cuttings and flooding resulted in greater biological N_2 fixation, 307 and 209 kg N ha^{-1} by *Sesbania rostrata* and *S. cannabina* respectively. Thus, *S. rostrata* can be used as a green manure by planting the stem-cuttings under flooded conditions[24].

Table 1. Regional examples of soil-fertility enhancement in multifunctional agroforestry systems in India

Region	Challenge	Changes observed due to agroforestry
Himalayas (Kurukshetra)[69]	Improvement of sodic soils	Increase in microbial biomass, tree biomass and soil carbon; enhanced nitrogen availability
Himalayas[19]	Restoration of abandoned agricultural sites	Biomass accumulation (3.9 t ha^{-1} in agroforests compared to 1.1 t ha^{-1} in degraded forests); improvement in soil physico-chemical characteristics; carbon sequestration
Western Himalayas[70]	Reducing soil and water loss in agroecosystems in steep slopes	Contour tree-rows (hedgerows), reduced run-off and soil loss by 40 and 48% respectively (in comparison to 347 mm run-off, 39 Mg ha^{-1} soil loss per year under 1000 mm rainfall conditions)
Sikkim Himalaya[71,72]	Enhancing litter production and soil nutrient dynamics	Nitrogen-fixing trees increase N and P cycling through increased production of litter and influence greater release of N and P; nitrogen-fixing species help in maintenance of soil organic matter, with higher N mineralization rates in agroforestry systems
Indo-Gangetic Plains (UP)[73]	Biomass production and nutrient dynamics in nutrient-deficient and toxic soils	Biomass production (49 t ha^{-1}/decade)
Himalayas (Meghalaya)[74]	Enhancing tree survival and crop yield	Crop yield did not decrease in proximity to *Albizzia* trees
Western India (Karnal)[75]	Improvement of soil fertility of moderately alkaline soils	Microbial biomass C which was low in rice–berseem crop (96.14 gg^{-1} soil) increased in soils under tree plantation (109.12 gg^{-1} soil); soil carbon increased by 11–52% due to integration of trees and crops
Western India (Rajasthan)[76]	Compatibility of trees and crops	Density of 417 trees per ha was found ideal for cropping with pulses
Central India (Raipur)[77]	Biomass production in N and P-stressed soils	*Azadirachta indica* trees were found to produce biomass in depleted soils
Central India[78]	Soil improvement	Decline in proportion of soil sand particles; increase in soil organic C, N, P and mineral N
Southern India (Hyderabad)[79]	Optimality of fertilizer use	
Southern India (Kerala)[80]	Growing commercial crops and trees	Ginger in interspaces of *Ailanthus triphysa* (2500 trees ha^{-1}) helps in getting better rhizome development of the former compared to solo cropping

Through a combination of mulching and water conservation, trees in agroecosystems may directly enhance crop yields of coarse grains. For instance, in the arid region of Haryana, the effect of *Prosopis cineraria*, *Tecomella undulata*, *Acacia albida* and *Azadirachta indica* on the productivity of *Hordeum vulgare* (barley) was found to be positive. *P. cineraria* enhanced grain yield by 86.0%, *T. undulata* by 48.8%, *A. albida* by 57.9% and *A. indica* by 16.8% over the control. Biological yield was also higher under trees than that in the open area. Soils under different tree canopies were rich in organic carbon content, moisture availability and nutrient status[25].

Recent studies have found that multiple-use species such as *Bambusa nutans* have the potential to help in soil nutrient binding during restoration of abandoned shifting agricultural lands (jhum fallows) in northeastern India under *B. nutans*. A comparison of jhum cultivation and agroforestry suggests that the latter is an option to address the challenges of slash-and-burn[26].

A study of nutrient cycling, nutrient use efficiency and nitrogen fixation in *Alnus*–cardamom plantations in the eastern Himalaya found that nutrient standing stock, uptake and return were highest in the 15-yr-old stand. Annual N fixation increased from the five-yr-old stand (52 kg ha^{-1}) to the 15-yr-old stand (155 kg ha^{-1}) and then declined with advancing age. Thus, *Alnus*–cardamom plantations performed sustainably up to 15–20 years[27].

There is robust evidence that agroforestry systems have the potential for improving water use efficiency by reducing the unproductive components of the water balance (run-off, soil evaporation and drainage)[28]. Examples from India and elsewhere show that simultaneous agroforestry systems could double rainwater utilization compared to annual cropping systems, mainly due to temporal complementarity and use of run-off in arid monsoon regions[29,30]. For instance, a combination of crops and trees uses the soil water between the hedgerows more efficiently than the sole cropped trees or crops, as water uptake of the trees reached deeper and started earlier after flood irrigation than that of the *Sorghum* crop, whereas the crop could better utilize topsoil water[31]. Integration of persistent perennial species with traditional agriculture also provides satisfactory drainage control to ameliorate existing outbreaks of salinity[32]. Agroforestry systems can also be useful for utilization of sewage-contaminated wastewater from urban systems[33].

It must be pointed out that although agroforestry systems may reduce crop yield for a variety of reasons, there may be a trade-off. For instance, studies on traditional agroforestry system in Central India[34] found that the effect of residual nitrogen on the yield of rice crop after removal of 15-yr-old *Acacia nilotica* trees resulted in increase in crop yield (12.5 t ha^{-1}) that was almost equal to the reduction in crop yield suffered during 15 years of tree growth in the agroforestry system. Yield reductions may also be compensated in the long run by microclimate modification[35].

Even when trees are not removed through total harvest, the species combination may be designed for nutrient release that benefits crops. Chemical characteristics and decomposition patterns of six multipurpose tree species, viz. *Alnus nepalensis*, *Albizzia lebbek*, *Boehmeria rugulosa*, *Dalbergia sissoo*, *Ficus glomerata* and *F. roxburghii* in a mixed plantation established on an abandoned agricultural land in a village at 1200 m altitude in Central Himalaya, is a case in point[36]. These species gave the highest rates of N and P release during the rainy season. Thus, *kharif* crops (rainy-season crops) are unlikely to be nutrient-stressed, even if leaf litter is the sole source of nutrients to crops in mixed agroforestry. A diverse multipurpose tree community provides not only diverse products, but may also render stable nutrient cycling[36].

Biodiversity conservation

Society needs to craft synergies among sustainable livelihoods, the Kyoto Protocol, the Convention on Biological Diversity, and other international instruments. Genetic diversity of landraces and trees in agroecosystems is particularly of immediate concern as there is a danger of erosion in ethnocultivars as well as knowledge that has generated such diversity[37]. Using agroforestry systems as carbon sinks, and by designing a suitable emissions trading system, the Kyoto Protocol provides a new source of financial support for protection and management of biological diversity[38].

Continued deforestation is a major challenge for forests and livelihoods. In addition, decreasing biological diversity through species reduction in managed agroforestry systems is also emerging as a challenge. Although agroforestry may not entirely reduce deforestation[39], in many cases it acts as an effective buffer to deforestation. Trees in agroecosystems in Rajasthan and Uttaranchal have been found to support threatened cavity-nesting birds, and offer forage and habitat to many species of birds[40]. These systems also act as a refuge to biodiversity after catastrophic events such as fire[41]. Agroforestry also leads to a more diversified and sustainable rural production system than many treeless farming alternatives and provides increased social, economic and environmental benefits for land users at all levels. What constitutes enough biodiversity in agroecosystems depends upon the goal in question and will differ depending on whether the aim is to increase yields to support livelihood improvement or deal with salinity, ground-water levels, soil erosion, leaching of nutrients or weed control.

If we are concerned about conserving important biodiversity, then protected areas are the preferred choice, and biodiversity conservation may not be a primary goal of agroforestry systems. Nevertheless, in some cases agroforestry systems do support as high as 50–80% of biodiversity of comparable natural systems[42], and also act as buffers to parks and protected areas. Landscape mosaics created by the interplay of rainwater harvesting as an adaptation to climate change and consequent growth of vegetation in agroforestry systems[43,44] act as a corridor providing avenues for dispersal and gene flow in wildlife population[45]. An example of buffer is provided by agroforestry around Hyderabad–Secunderabad. Biomass assessment within 100 km radius of twin cities suggests that annual increment of trees and forests in the region approximately equals the estimated annual wood and fuelwood intake of cities and villages[46]. This supply has acted to buffer the pressure on natural forests.

Tree diversity indeed can be large in some Indian village ecosystems. A study in Sirsimakki village of Karnataka by Shastri *et al.*[47] found 952 individuals belonging to 93 species in just 1.7 ha of agroecosystem. An additional 44 species on non-agricultural lands in the village ecosystem that included 'soppina betta', minor forest and reserve forest were found. The overall agroecosystem had more trees (556 trees/ha) and diversity (diversity index 3.5) compared to the non-agro ecosystem that had 354 trees/ha and a species diversity of 3.87. The overall village ecosystem tree density of 418.8 per ha, with 144 species in 2238 individuals in the sampled area of 5.34 ha is a useful resource. Furthermore, home-gardens, with tree species varying between 20 and 40 on each unit and with an average area of 376 m^2, support in all 93 tree species counted in just 1.7 ha.

Thus, although not a substitute for continuous and intact natural systems, fragments of all sizes and shapes, nonetheless, have conservation relevance. Local farmers who plant trees on their small farms are often surprised later by the number of birds and small mammals that begin to populate the area.

Biological pest control

Agroforestry systems create a landscape structure that is important for biological pest control. In small-scale, subsistence agriculture in the tropics, traditional farming practices have evolved that provide a sustainable means of reducing the incidence and damage caused by pests, including nematodes. The biodiversity inherent in multiple cropping and multiple cultivar traditional farming systems increases the available resistance or tolerance to

nematodes[48]. In structurally complex landscapes, parasitism is higher and crop damage lower than in simple landscapes with a high percentage of agricultural use[49].

Breaking the poverty and food insecurity circle

Agroforestry could contribute to livelihood improvement in India, where people have a long history and accumulated local knowledge. India is particularly notable for ethnoforestry practices and indigenous knowledge systems on tree-growing. In terms of household income, Central Indian upland rice fields provide an illuminating economics[50]. The farms often have an average of 20 *Acacia nilotica* trees per ha, of 1 to 12 years of age. Small farms have more tree density. At a ten-year rotation, these trees provide a variety of products, including fuelwood (30 kg/tree), brushwood for fencing (4 kg/tree), small timber for farm implements and furniture (0.2 m^3), and non-timber forest products such as gum and seeds. Thus, trees account for nearly 10% of the annual farm income – distributed uniformly throughout the year than in rice monoculture – of smallholder farmers with less than 2 ha farm holding. A combination of *Acacia* and rice traditional agroforestry system has a benefit/cost (B/C) ratio of 1.47 and an internal rate of return (IRR) of 33% at 12% annual discount rate during a ten-year period.

In the northeast Indian State of Meghalaya, guava and Assam lemon-based agrihorticultural agroforestry systems (i.e. farming systems that combine domesticated fruit trees and forest trees) gave 2.96 and 1.98-fold higher net return respectively, in comparison to farmlands without trees. Average net monetary benefit to guava-based agroforestry systems was Rs 20,610/ha (US$ 448.00) and to Assam lemon-based agroforestry systems, Rs 13,787.60/ha (US$ 300.00). Such systems are most useful livelihood improvement strategies in the rainfed agriculture of Meghalaya[51]. Similarly, the net present value for the different agroforestry models on six-year rotation in Haryana varied from Rs 26,626 to Rs 72,705 ha^{-1} yr^{-1}, whereas the B/C ratio and IAR varied from 2.35 to 3.73 and 94 to 389% respectively. Thus, agroforestry has not only uplifted the socio-economic status of farmers, but also contributed towards the overall development of the region[52].

There are numerous non-timber forest products collected from wilderness for subsistence and cash income. Often, harvesting is unsustainable because of lack of knowledge about silviculture of species and destructive exploitation strategies driven by market forces. Domestication of such species aimed at commercialization and production of valued products can reduce the pressure on natural ecosystems[53].

Domestication of forest fruit trees and other species grown in agroforestry systems offers significant opportunity for livelihood improvement through nutritional and economic security of the poor in the tropics[54]. The wild edible plants form an important constituent of traditional diet in Sikkim Himalaya, where about 190 species are eaten and almost 47 species are traded in local market. Wild edible fruit species have high carbohydrate content[55] ranging between 32 and 88%. Such fruit trees can be taken up for domestication in agroecosystems on priority action.

Trees in agroforestry systems can provide host to globally valued products and thus support livelihoods locally. A study of the 8-yr-old agroforestry intervention in Palamau District, Jharkhand found that the community depended solely on rainfed farming and animal husbandry definitely gains positively by agroforestry interventions[56]. Suitable community plantations of non-timber forest products in tribal areas such as Jharkhand can potentially serve the dual purpose of conserving useful species as well as livelihood improvement of local people[57]. Such programmes in tribal areas have enhanced likelihood of success as communities are dependent on the wild resources for livelihood. In Jharkhand, trees in agroecosystems are particularly valued as host to insects that yield marketable products such as silk[58], lac products[59] and honey[60].

Woodcarving industry is emerging as an important source of income to local artisans worldwide[61]. Promotion of species used in woodcarving industry facilitates long-term locking-up of carbon in carved wood and supports local knowledge. It therefore strengthens livelihoods. For example, Jodhpur, Rajasthan has emerged as a major centre of woodcarving, exporting woodcraft worth Rs 60 million annually, facilitated by traditional knowledge and skill, and growing tourism. Suitable agroforestry programmes may enhance the availability of wood in agroecosystems, thereby improving the ability of developing countries to participate in the growing global economy.

Caveats and clarifications

All nature–society interactions have trade-offs and agroforestry systems are no exception. Although agroforestry is a useful land-use management option, it requires careful planning and studies on the remaining challenges, such as farm yield decline under agroforestry systems.

There may not be an entirely convincing rationale for the argument that agroforestry systems are the answer for livelihood improvement. Nevertheless, this review does provide some pointers in that direction. Although, over the last twenty-five years of research in India has demonstrated the potential of agroforestry and some practices have been widely adopted, the vast potential is yet to be fully exploited[62]. Research is needed to further refine the key points of agreement and also to fill the crucial knowledge gaps (Table 2). There is, evidently, a major gap in our understanding of how agroforestry systems contribute to/fit into rural livelihood improvement. Future research is required to remove many of the uncertainties that remain, and also carefully test the main functions attributed to agroforestry against alternative land-use options in order

Table 2. Unresolved challenges for future agroforestry research and innovations in India

Crop yields: increase or decrease?	Although some traditional agroforestry systems do increase crops yields near trees, there are instances where fast-growing trees have reduced crop yield in the short term. Long-term studies are required to resolve this issue.
Nutrients: additional supply or redistribution?	Mature and scattered agroforestry trees are associated with improved soil nutrient supply in traditional agroforestry systems. It is not known if trees additionally supply nutrients by increasing the total quantum of nutrients in agroecosystems or just redistribute the available quantity horizontally and vertically.
Water–tree interaction: high water uptake or no change?	High water use by fast-growing species and therefore alleged groundwater depletion is a common concern in dry regions that remains unresolved. Do trees actually extract more groundwater or use the residual water available either through irrigation, or use rainwater when crops have been harvested? It may be possible that rather than letting the rains be lost as run-off, agroforestry may increase the utilization of rainwater by extending the growing season. Furthermore, it is not clearly understood if trees harvest and accumulate water from surrounding area and release it during the soil-moisture stress. If this is so, then, agroforestry as an adaptation to monsoon variability may actually benefit the crops.
Carbon sequestration in biomass and soils	Studies on carbon sequestration potential are limited both by their location-specificity as well as uncertainty related to sequestration in biomass and soils. Often, the rate of carbon sequestration is derived from the growth of above-ground biomass. Holistic insights are required on carbon sequestration by agroforestry systems.
Soil amelioration and conservation	Agroforestry systems with mature trees capable of yielding enough litter are known to conserve soils and ameliorate soil nutrient status, but knowledge on the full range of species and their attributes useful for all the agro-climatic regions and problem-soils in India is required.
Genetically improved trees	Genetically improved trees may provide more biomass and other products valued by the society, but presently research results in this field mostly remain in the laboratory. A full mechanism starting from developing and registration of clones, decentralized certification, and mass multiplication of suitable stock to ensure availability to farmers is required.
Multiple-use species adapted to multiple agro-climatic conditions	Multiple-use species with a wide range of geographic and climatic adaptation can enhance the success and spread of agroforestry. This is a crucial area of research involving multi-location research in all the climatic regions in India.
Domestication of useful species	Many wild populations of species that yield commercially-valued products are getting depleted. Research efforts are required to domesticate these species and integrate with the agroforestry systems in India.
Policies to promote linkages between markets and tree-growing in agroecosystems	On the one hand, smallholder systems in India supply about 50% of wood and fuelwood demand. On the other hand, there are still many restrictive regulations that potentially deter farmers from growing trees in agroecosystems and selling these in the markets.
Value-addition innovations	Non-timber forest products have the potential to improve livelihoods of poor farmers, but vigorous efforts are needed to provide knowledge on the on-farm value-addition innovation.

to know unequivocally as to what extent agroforestry has served these purposes.

Agroforestry practices are strongly dependent on access to land within the community. Households that do not have ownership to lands may not be able to benefit from the agroforestry interventions for livelihood improvement, unless market regimes permit their inclusion through value-addition services.

Trees in a variety of ethnoforestry and agroforestry systems contribute to food security, rural income generation through diversity of products and services, and can enhance nutrient cycling, improve soil productivity, soil conservation and soil faunal activities. Nonetheless, trees in agroforestry systems can also cause competition with the associated food crops. Agroforestry may, thus, reduce the yield of the agricultural produce in farmlands. For instance, in Haryana, *A. indica* and *P. cineraria* did not produce any significant difference in the wheat yield, while *Dalbergia sissoo* and *Acacia nilotica* gave a reduction in yield. *A. nilotica* had a more prominent effect with a reduction of 40 to 60% wheat yield and *D. sissoo* reduced yield by 4 to 30%, but the reduction effect[63] was only up to a distance of 3 m. Interestingly, species that did not negatively affect the yield are indigenous trees occurring in traditional agroforestry systems, and they are economically more useful for providing multiple benefits. Selection of such species to enrich agroforestry systems shall be useful for local and national food security.

Not all species desirable for livelihood improvement can be grown without designing an optimum species combination. Many fruit-yielding species that are suitable to tolerate highly alkali soil (pH > 10) become susceptible to waterlogging. The desirability for agroforestry systems due to high potential for livelihood improvement requires special techniques for planting. For example, pomegranate (*Punica granatum*) trees are unable to tolerate water

stagnation. To avoid mortality due to water stagnation during the monsoon, the raised and sunken bed technique may be necessary for agroforestry practices on highly alkali soil[64].

Designing a sustainable tree mixture for agroforestry systems is another challenge. In agroforestry, differences in functional group composition do have a larger effect on ecosystem processes than does functional group richness alone. Thus, much time and expense need to be invested in finding species or genetic varieties that combine in more diverse agroecosystems to improve total yield. For instance, a five-year field experiment of tree mixtures for agroforestry system in tropical alfisol of southern India involving mango (*Mangifera indica*), sapota (*Achrus sapota*), eucalyptus (*Eucalyptus tereticornis*), casuarina (*Casuarina equisetifolia*) and leucaena (*Leucaena leucocephala*) found that growth of sapota can be enhanced by 17% when grown in mixture with leucaena. But a reduction of 12% in the growth of mango may occur when co-planted with casuarina or leucaena[65]. Eucalyptus is incompatible with mango and sapota. Many species suffer from root competition and thus selection of tree species with either low root competitiveness or trees with complementary root interaction is of strategic importance in agroforestry systems[66].

The future

Although numerous issues are involved with livelihood improvement, agroforestry systems are one option with multifunctional value. In India and other developing countries, the path to sustainable development could be a decentralized planning and implementation of strategies that promote local biomass production in agroforestry systems. Such decentralized systems in India can provide critical inputs for livelihood improvement and sustainable development. Along with mitigating the climate change, agroforestry systems can at least partially meet the energy needs of one billion people in India through bioenergy options, by a prudent use of agricultural residues and biomass generated in agroforestry systems. Biomass energy-based supply options can create rural wealth and employment necessary for livelihood improvement and sequester large amount of carbon in a decentralized manner. Such a strategy would also ensure ecological, economic and social well-being. Thus, an energy and food self-sufficient taluka (a small administrative unit) can be a new model of rural development in India[67].

Although agroforestry options for carbon sequestration are attractive, they present critical challenges for carbon and cost accounting due to dispersed nature of farmlands and dependence of people on the multiple benefits from agroforestry. Additionally, important concerns regarding monitoring, verification, leakage and the establishment of credible baselines also need to be addressed.

Another challenge is the incentives that promote tree-growing by rural people. Not everyone is willing to adopt agroforestry. We shall need effective communication strategy to extend innovations among people to adopt and maintain agroforestry to supply fuelwood and other products. The likelihood of adoption depends on the availability of lands, progressive attitude of farmers, supportive village institutions, their wealth status and their perceived risk concerning agricultural production[68].

In conclusion, in order to use agroforestry systems as an important option for livelihood improvement, climate-change mitigation and sustainable development in India, research, policy and practice will have to progress towards: (i) effective communication with people in order to enhance agroforestry practices with primacy to multifunctional values; (ii) maintenance of the traditional agroforestry systems and strategic creation of new systems; (iii) enhancing the size and diversity of agroforestry systems by selectively growing trees more useful for livelihood improvement; (iv) designing context-specific silvicultural and farming systems to optimize food production, carbon sequestration, biodiversity conservation; (v) maintaining a continuous cycle of regeneration-harvest–regeneration as well as locking the wood in non-emitting uses such as woodcarving and durable furniture; (vi) participatory domestication of useful fruit tree species currently growing in wilderness to provide more options for livelihood improvement, and (vii) strengthening the markets for non-timber forest products. Prevalence of a variety of traditional agroforestry systems in India offers opportunity worth reconsidering for carbon sequestration, livelihood improvement, biodiversity conservation, soil fertility enhancement and poverty reduction.

1. Ellis, F., *Rural Livelihoods and Diversity in Developing Countries*, Oxford University Press, Oxford, 2000.
2. Sayer, J. A. and Campbell, B. M., *The Science of Sustainable Development: Local Livelihoods and the Global Environment*, Cambridge University Press, Cambridge, UK, 2004, p. 268.
3. Carney, D. (ed.), *Sustainable Rural Livelihoods: What Contribution Can We Make?* Department for International Development, London, 1998.
4. Belcher, B., Forest product markets, forests and poverty reduction. *Int. For. Rev.*, 2005, **7**, 82–89.
5. Pandey, D. N., *Beyond Vanishing Woods: Participatory Survival Options for Wildlife, Forests and People*, Himanshu/CSD, New Delhi, 1996, p. 222.
6. AFD, ADB, DFID *et al*., *Poverty and Climate Change: Reducing the Vulnerability of the Poor Through Adaptation*, DFID, London, 2003.
7. Pandey, D. N., Carbon sequestration in agroforestry systems. *Climate Policy*, 2002, **2**, 367–377.
8. Pandey, N., Societal adaptation to abrupt climate change and monsoon variability: Implications for sustainable livelihoods of rural communities. Report, Winrock International – India, New Delhi, 2005.
9. Bawa, K. S. *et al*., Tropical ecosystems into the 21st century. *Science*, 2004, **306**, 227–228.
10. Pandey, D. N., *Ethnoforestry: Local Knowledge for Sustainable Forestry and Livelihood Security*, Himanshu/AFN, New Delhi, 1998.
11. Bowonder, B., Prasad, S. S. R. and Unni, N. V. M., Dynamics of fuelwood prices in India: Policy implications. *World Dev*., 1988, **16**, 1213–1229.

12. Ravindranath, N. H. and Hall, D. O., *Biomass, Energy and Environment: A Developing Country Perspective from India*, Oxford University Press, New York, 1995, p. 376.
13. Prasad, R., Pandey, D. N. and Kotwal, P. C., *Trees Outside Forests in India: A National Assessment*, Indian Institute of Forest Management, Bhopal, 2000.
14. *National Forestry Action Programme*, Ministry of Environment and Forests, Government of India, New Delhi, 1999, vols 1 & 2.
15. Rai, S. N. and Chakrabarti, S. K., Demand and supply of fuelwood and timber in India. *Indian For.*, 2001, **127**, 263–279.
16. Makundi, W. R. and Sathaye, J. A., GHG mitigation potential and cost in tropical forestry – relative role for agroforestry. *Environ. Dev. Sustain.*, 2004, **6**, 235–260.
17. Albrecht, A. and Kandji, S. T., Carbon sequestration in tropical agroforestry systems. *Agric. Ecosyst. Environ.*, 2003, **99**, 15–27.
18. Sathaye, J. A. and Ravindranath, N. H., Climate change mitigation in the energy and forestry sectors of developing countries. *Annu. Rev. Energy Environ.*, 1998, **23**, 387–437.
19. Maikhuri, R. K., Semwal, R. L., Rao, K. S., Singh, K. and Saxena, K. G., Growth and ecological impacts of traditional agroforestry tree species in Central Himalaya, India. *Agrofor. Syst.*, 2000, **48**, 257–271.
20. Montagnini, F. and Nair, P. K. R., Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agrofor. Syst.*, 2004, **61/62**, 281–295.
21. Myers, N., The next green revolution: Its environmental underpinnings. *Curr. Sci.*, 1999, **76**, 507–513.
22. Rasmussen, P. E. *et al.*, Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. *Science*, 1998, **282**, 893–896.
23. Manna, M. C., Ghosh, P. K. and Acharya, C. L., Sustainable crop production through management of soil organic carbon in semiarid and tropical India. *J. Sustain. Agric.*, 2003, **21**, 87–116.
24. Patel, L. B., Sidhu, B. S. and Beri, V., Symbiotic efficiency of *Sesbania rostrata* and *S. cannabina* as affected by agronomic practices. *Biol. Fert. Soils*, 1996, **21**, 149–151.
25. Kumar, A., Hooda, M. S. and Bahadur, R., Impact of multipurpose trees on productivity of barley in arid ecosystem. *Ann. Arid Zone*, 1998, **37**, 153–157.
26. Arunachalam, A., Khan, M. L. and Arunachalam, K., Balancing traditional jhum cultivation with modern agroforestry in eastern Himalaya – A biodiversity hot spot. *Curr. Sci.*, 2002, **83**, 117–118.
27. Sharma, G., Sharma, R., Sharma, E. and Singh, K. K., Performance of an age series of *Alnus*–cardamom plantations in the Sikkim Himalaya: Nutrient dynamics. *Ann. Bot.*, 2002, **89**, 273–282.
28. Turner, N. C. and Ward, P. R., The role of agroforestry and perennial pasture in mitigating water-logging and secondary salinity: Summary. *Agric. Water Manage.*, 2002, **53**, 271–275.
29. Lövenstein, H. M., Berliner, P. R. and van Keulen, H., Runoff agroforestry in arid lands. *For. Ecol. Manage.*, 1991, **45**, 59–70.
30. Droppelmann, K. and Berliner, P., Runoff agroforestry – A technique to secure the livelihood of pastoralists in the Middle East. *J. Arid Environ.*, 2003, **54**, 571–577.
31. Lehmann, J. *et al.*, Below-ground interactions in dryland agroforestry. *For. Ecol. Manage.*, 1998, **111**, 157–169.
32. Dunin, F. X., Integrating agroforestry and perennial pastures to mitigate water-logging and secondary salinity. *Agric. Water Manage.*, 2002, **53**, 259–270.
33. Bradford, A., Brook, R. and Hunshal, C. S., Wastewater irrigation in Hubli–Dharwad, India: Implications for health and livelihoods. *Environ. Urban.*, 2003, **15**, 157–170.
34. Pandey, C. B. and Sharma, D. K., Residual effect of nitrogen on rice productivity following tree removal of *Acacia nilotica* in a traditional agroforestry system in central India. *Agric. Ecosyst. Environ.*, 2003, **96**, 133–139.
35. Kohli, A. and Saini, B. C., Microclimate modification and response of wheat planted under trees in a fan design in northern India. *Agrofor. Syst.*, 2003, **58**, 109–117.
36. Semwal, R. L., Maikhuri, R. K., Rao, K. S., Sen, K. K. and Saxena, K. G., Leaf litter decomposition and nutrient release patterns of six multipurpose tree species of central Himalaya, India. *Biomass Bioenergy*, 2003, **24**, 3–11.
37. Maxted, N., Guarino, L., Myer, L. and Chiwona, E. A., Towards a methodology for on-farm conservation of plant genetic resources. *Genet. Resour. Crop Evol.*, 2002, **49**, 31–46.
38. Walsh, M. J., Maximizing financial support for biodiversity in the emerging Kyoto protocol markets. *Sci. Total Environ.*, 1999, **240**, 145–156.
39. Angelsen, A. and Kaimowitz, D., Is agroforestry likely to reduce deforestation? In *Agroforestry and Biodiversity Conservation in Tropical Landscapes* (eds Schroth, G. *et al.*), Island Press, Washington, DC, 2004, pp. 87–106.
40. Pandey, D. N. and Mohan, D., Nest site selection by cavity nesting birds on *Melia azedarach* L. and management of multiple use forests. *J. Bombay Nat. Hist. Soc.*, 1993, **90**, 58–61.
41. Griffith, D. M., Agroforestry: A refuge for tropical biodiversity after fire. *Conserv. Biol.*, 2000, **14**, 325–326.
42. Noble, I. R. and Dirzo, R., Forests as human-dominated ecosystems. *Science*, 1997, **277**, 522–525.
43. Pandey, D. N., A bountiful harvest of rainwater. *Science*, 2001, **293**, 1763.
44. Pandey, D. N., Gupta, A. K. and Anderson, D. M., Rainwater harvesting as an adaptation to climate change. *Curr. Sci.*, 2003, **85**, 46–59.
45. Pandey, D. N., Global climate change and carbon management in multifunctional forests. *Curr. Sci.*, 2002, **83**, 593–602.
46. Unni, N. V. M., Naidu, K. S. M. and Kumar, K. S., Significance of landcover transformations and the fuelwood supply potentials of the biomass in the catchment of an Indian metropolis. *Int. J. Remote Sensing*, 2000, **21**, 3269–3280.
47. Shastri, C. M., Bhat, D. M., Nagaraja, B. C., Murali, K. S. and Ravindranath, N. H., Tree species diversity in a village ecosystem in Uttara Kannada district in Western Ghats, Karnataka. *Curr. Sci.*, 2002, **82**, 1080–1084.
48. Bridge, J., Nematode management in sustainable and subsistence agriculture. *Annu. Rev. Phytopathol.*, 1996, **34**, 201–225.
49. Thies, C. and Tscharntke, T., Landscape structure and biological control in agroecosystems. *Science*, 2000, **285**, 893–895.
50. Viswanath, S., Nair, P. K. R., Kaushik, P. K. and Prakasam, U., *Acacia nilotica* trees in rice fields: A traditional agroforestry system in central India. *Agrofor. Syst.*, 2000, **50**, 157–177.
51. Bhatt, B. P. and Misra, L. K., Production potential and cost–benefit analysis of agrihorticulture agroforestry systems in Northeast India. *J. Sustain. Agric.*, 2003, **22**, 99–108.
52. Kumar, R., Gupta, P. K. and Gulati, A., Viable agroforestry models and their economics in Yamunanagar District of Haryana and Haridwar District of Uttaranchal. *Indian For.*, 2004, **130**, 131–148.
53. Belcher, B., Ruíz-Pérez, M. and Achdiawan, R., Global patterns and trends in the use and management of commercial NTFPs: Implications for livelihoods and conservation. *World Dev.*, 2005, **33**, 1435–1452.
54. Milne, G. *et al.*, *Unlocking Opportunities for Forest-Dependent People in India*, Agriculture and Rural Development Sector Unit, South Asia Region, The World Bank/Oxford University Press, New Delhi, 2006.
55. Sundriyal, M. and Sundriyal, R. C., Wild edible plants of the Sikkim Himalaya: Nutritive values of selected species. *Econ. Bot.*, 2001, **55**, 377–390.
56. Minj, A. V. and Quli, S. M. S., Impact of agroforestry on socioeconomic status of respondents. *Indian For.*, 2000, **126**, 788–791.
57. Quli, S. M. S., Agroforestry for NTFPs conservation and economic upliftment of farmers. *Indian For.*, 2001, **127**, 1251–1262.
58. Singh, M. P., Dayal, N. and Singh, B. S., Importance of genetic conservation of tasar host plants in agroforestry programme in Chhotanagpur region of Bihar. *J. Palynol.*, 1994, **30**, 157–163.

59. Jaiswal, A. K., Sharma, K. K., Kumar, K. K. and Bhattacharya, A., Households survey for assessing utilisation of conventional lac host trees for lac cultivation. *New Agric.*, 2002, **13**, 13–17.
60. Dwivedi, M. K., Apiculture in Bihar and Jharkhand: A study of costs and margins. *Agric. Market.*, 2001, **44**, 12–14.
61. Cunningham, A., Campbell, B. and Belcher, B. (eds), *Carving out a Future: Forests, Livelihoods and the International Woodcarving Trade*, Earthscan, London, UK, 2005.
62. Puri, S. and Nair, P. K. R., Agroforestry research for development in India: 25 years of experiences of a national program. *Agrofor. Syst.*, 2004, **61/62**, 437–452.
63. Puri, S., Bangarwa, K. S. and Singh, S., Influence of multipurpose trees on agricultural crops in arid regions of Haryana, India. *J. Arid Environ.*, 1995, **30,** 441–451.
64. Dagar, J. C., Sharma, H. B. and Shukla, Y. K., Raised and sunken bed technique for agroforestry on alkali soils of northwest India. *Land Degrad. Dev.*, 2001, **12**, 107–118.
65. Swaminathan, C., Sustainable tree mixtures: Optimum species combination for a tropical alfisol of southern India. *Biol. Agric. Hortic.*, 2001, **18**, 259–268.
66. Kumar, S. S., Kumar, B. M., Wahid, P. A., Kamalam, N. V. and Fisher, R. F., Root competition for phosphorus between coconut, multipurpose trees and kacholam (*Kaempferia galanga* L.) in Kerala, India. *Agrofor. Syst.*, 1999, **46**, 131–146.
67. Rajvanshi, A. K., Talukas can provide critical mass for India's sustainable development. *Curr. Sci.*, 2002, **82**, 632–637.
68. Mahapatra, A. K. and Mitchell, C. P., Biofuel consumption, deforestation, and farm level tree growing in rural India. *Biomass Bioenergy*, 1999, **17**, 291–303.
69. Kaur, B., Gupta, S. R. and Singh, G., Carbon storage and nitrogen cycling in silvopastoral systems on a sodic in northwestern India. *Agrofor. Syst.*, 2002, **54**, 21–29.
70. Narain, P., Singh, R. K., Sindhwal, N. S. and Joshie, P., Agroforestry for soil and water conservation in the western Himalayan Valley Region of India 1. Runoff, soil and nutrient losses. *Agrofor. Syst.*, 1997, **39**, 175–189.
71. Sharma, R., Sharma, E. and Purohit, A. N., Cardamom, mandarin and nitrogen-fixing trees in agroforestry systems in India's Himalayan region. I. Litterfall and decomposition. *Agrofor. Syst.*, 1996, **35**, 239–253.
72. Sharma, R., Sharma, E. and Purohit, A. N., Cardamom, mandarin and nitrogen-fixing trees in agroforestry systems in India's Himalayan region. II. Soil nutrient dynamics. *Agrofor. Syst.*, 1996, **35**, 255–268.
73. Singh, B., Biomass production and nutrient dynamics in three clones of *Populus deltoides* planted on Indo-gangetic plains. *Plant Soil*, 1998, **203**, 15–26.
74. Dhyani, S. K. and Tripathi, R. S., Tree growth and crop yield under agrisilvicultural practices in north-east India. *Agrofor. Syst.*, 1998, **44**, 1–12.
75. Kaur, B., Gupta, S. R. and Singh, G., Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. *Appl. Soil Ecol.*, 2000, **15**, 283–294.
76. Gupta, G. N., Singh, G. and Kachwaha, G. R., Performance of *Prosopis cineraria* and associated crops under varying spacing regimes in the arid zone of India. *Agrofor. Syst.*, 1998, **40**, 149–157.
77. Puri, S. and Swamy, S. L., Growth and biomass production in *Azadirachta indica* seedlings in response to nutrients (N and P) and moisture stress. *Agrofor. Syst.*, 2001, **51**, 57–68.
78. Pandey, C. B., Singh, A. K. and Sharma, D. K., Soil properties under *Acacia nilotica* trees in a traditional agroforestry system in central India. *Agrofor. Syst.*, 2000, **49**, 53–61.
79. Osman, M., Emminhgam, W. H. and Sharrow, S. H., Growth and yield of sorghum or cowpea in an agrisilviculture system in semi-arid India. *Agrofor. Syst.*, 1998, **42**, 91–105.
80. Kumar, B. M., Thomas, J. and Fisher, R. F., *Ailanthus triphysa* at different density and fertiliser levels in Kerala, India: Tree growth, light transmittance and understorey ginger yield. *Agrofor. Syst.*, 2001, **52**, 133–144.

ACKNOWLEDGEMENTS. I am grateful to the anonymous reviewers for insightful suggestions. Critical reviews by Dr Grant Milne and Dr Peter Jipp, PROFOR/World Bank, Washington, DC; Dr Brian Belcher, Center for International Forestry Research, Indonesia, and Prof. N. H. Ravindranath, Indian Institute of Science, Bangalore on an earlier version of the manuscript are acknowledged. The views expressed in this article are those of the author and not necessarily those of the Center for International Forestry Research, Indonesia.

Received 21 May 2005; revised accepted 6 September 2006