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Role of *tao* (*Belotia mexicana*) in the traditional Lacandon Maya shifting cultivation ecosystem

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Abstract For centuries, the Lacandon Maya have farmed the forest while also preserving and regenerating it. The Lacandon manage their fallow by planting certain tree species, and removing volunteer trees that are not optimal for soil fertility. This study focused on *tao* (*Belotia mexicana*), one of the Lacandon tree fallow species, and its impact on the soil as it matures in the secondary forest. The effect of *tao* on soil fertility was evaluated using the following soil fertility parameters: phosphorus, carbon, nitrogen, earthworm density, pH, and soil moisture. Results were compared using a split-plot analysis. Soil C:N ratios decreased with age of *tao*, indicating an improvement of litter quality over time. Soil extractable phosphorus decreased with age of *tao* and increased with distance from *tao*, which suggests that *tao* is depleting phosphorus. These results provide an introduction for further analysis into how native trees enhance soil fertility in the Lacandon system.

Keywords Agroforestry · Swidden · Improved tree fallow · Traditional ecological knowledge · Chiapas

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Introduction

The Lacandon Rain Forest in Chiapas, Mexico, contains as much as 25% of Mexico's total species diversity (Howard and Homer-Dixon 1996; O'Brien 1998; Bobrow-Strain 2007).

Land areas of southern Mexico are losing productivity at alarming rates (Diemont et al. 2006; Mendoza and Dirzo 1999), largely due to deforestation and establishment of pasture for raising livestock (Mas and Puig 2001). Raising cattle is a common livelihood amongst migrant groups (Mendoza and Dirzo 1999), and migrant populations have drastically changed the ecological stability of the Lacandon Rain Forest (Diemont et al. 2006; Mas and Puig 2001). For the land that is still being used for agriculture, increasing population pressures have led to short-term fallows that do not allow the soil enough time to recuperate fertility (Szott et al. 1999).

For centuries, the Lacandon Maya have farmed the forest while also preserving and regenerating it (Nations and Nigh 1980; Diemont and Martin

2009). Traditional Mayan agriculture takes advantage of successional processes that replenish soil nutrients without fertilizer inputs. Lacandon traditional ecological knowledge (TEK) could greatly contribute to current sustainable agriculture practices. One documented method of enhancing soil is the practice of planting native tree species where soils have been intensively cultivated for a few years (Diemont et al. 2006; Diemont and Martin 2009; Levy Tacher et al. 2002; Levy Tacher and Golicher 2004). Diemont and Martin (2009) discerned six stages in the Lacandon agroforestry system: primary forest, an herbaceous stage (commonly known as *milpa*), two shrub stages (collectively known as the *acahual*), and two secondary forest stages (Diemont and Martin 2009). Lacandon stage names are used here. *Kor* is the herbaceous stage, a polyculture where upwards of 20 plants are cultivated. After 3–5 years, *kor* transitions to *robir*, a shrub stage. *Robir* lasts for 2 years, before the trees mature into *jurup che*, the second fallow shrub stage, which is a 2–3 year phase. Following *jurup che* are two secondary forest stages. The first is *mehen che*, and the second is *nu kux che*. *Mehen che* lasts for 10 years, after which it transitions to *nu kux che*, which can last from 5 to 20 years. The Lacandon believe that *nu kux che* eventually returns to primary forest. In less than 20 years following *kor*, the Lacandon are able to restore soil fertility and regenerate secondary forest (Diemont and Martin 2009).

This research contributes to previous studies that have examined native trees used by the Lacandon to restore soil fertility (Levy Tacher and Golicher 2004; Diemont et al. 2006). The leaves of *Ochroma pyramidale* inhibit nematodes, which suggests a hindrance of leaf decay that accelerates soil organic matter accumulation (Diemont et al. 2006). Extractable phosphorus under *Sapium lateriflorum* was 16% higher than outside the canopy, and increased with tree age, indicating P recovery from the subsoil (Diemont et al. 2006). These results encouraged additional research into the native trees the Lacandon are using during the fallow to restore their agricultural soils. This investigation focused on *tao* (*Belotia mexicana*), and the conditions in the soil supporting *tao* individuals growing in *mehen che* and *nu kux che*. The objective of this study was to better identify the influence of *tao* on the secondary forest soils in the Lacandon agroforestry system.

Materials and methods

Site

Soil sampling was conducted in Lacanja Chansayab, Mexico, located at 16°45′30″ N and 91°08′30″ W and at an elevation of 400 m. Sampling trees were located on one 79-ha property. With a population of approximately 400, Lacanja is one of three principal communities of the Lacandon Maya. The predominant soil type is Alfisol with a clayey texture and neutral pH. The study site's surrounding ecosystem is lower montane rainforest (Breedlove 1973), and annual rainfall is 2,500 mm (Diemont et al. 2006). All field work was conducted during three separate field trips in July, 2008, during the wet season.

Study species

In previous studies conducted by Diemont et al. (2006) and Diemont and Martin (2009), Lacandon farmers identified plants that assisted in soil fertility regeneration and restoration. From these lists and by consulting with landowners about tree availability, *tao* was chosen for this study. *Tao* is a common tree species (importance value ranges between 60 and 80% in secondary forests) in the lower montane rain forests of the Eastern Highlands of Chiapas (Breedlove 1973; Cheng 2009). *Tao* is used in construction, and competes successfully with grasses in degraded pasture (Aldolfo Chan Kin, Lacanja, pers comm). In addition to being a valued species in Lacandon fallow management, *tao* is used by other farmers in this region. *Tao* is planted in the mosaic of shade trees grown in Chiapas coffee plantations (Romero-Alvarado et al. 2002).

Sampling and analysis

Tao in *mehen che* and *nu kux che* fallows were used for sampling. Three representative fallows from each age class were sampled. Three trees were sampled at each site, for a total of 18 study trees. At each tree, a flag was placed at the canopy edge (E) in the north, east, south, and west directions. From the canopy edge, distance to the tree bark was measured and a flag was placed under the canopy at half that distance (marked I, for inside the canopy). That same distance was used to flag the area outside (O) the canopy. All twelve points were sampled using a soil corer at 0–20 cm depth, and samples were combined into three bags of mixed soil marked "I", "E", and "O". Soil samples combined the O and A horizons. At each sampling point, earthworm density was estimated. In the northern transect of each *tao*, earthworms were sampled at inside, at the edge of, and outside the crown. At each earthworm sampling point, a wooden frame measuring 10 × 10 × 7 cm was the uniform sampling unit (Peñuela and Drew 2004). The frame was pushed into the soil until the soil was flush with the top of the frame. The soil inside the frame was scooped onto a sheet of plastic and searched thoroughly for earthworms.

Soil C and N were analyzed using the Micro-Dumas method in the Thermo Scientific Flash EA 1112 Elemental Analyzer. Soils were tested for extractable phosphorus (P) using the Troug chemical extraction method and the Shimadzu UV-1800 spectrophotometer (Wilde et al. 1972).

Statistical analysis was conducted using SAS V8 computer software. Sampling points at different distances and ages were compared using an ANOVA split-plot design. In this design, age class (*nu kux che or mehen che*) was the two-level whole plot factor. The subplot factor was distance, containing three levels (inside, edge, and outside). At each of the 18 study trees, three composite soil samples were collected. The two treatments for the experiment are (1) age class and (2) distance from the tree. Simple effects were compared for differences using Tukey's test to control the experiment-wise error rate at $\alpha = 0.10$; this α level was chosen to increase power to detect differences in a highly diverse system, a decision that may lead to higher Type I error.

Results

As the fallow progresses from *mehen che* to *nu kux che*, extractable phosphorus appears to decrease (Table 1). Earthworm variability was high in both field stages. Most fertility indicators exhibited decreased variance in the older stage.

Age of *tao* had a significant effect on extractable P (P) ($P = 0.0001$, Table 2). As the tree ages, phosphorus decreases. Extractable P also increases with distance from the tree (Fig. 1).

Table 1 Means for soil response variables in *mehen che* (n = 27) and *nu kux che* (n = 27)

Response variable	Mehen che	Nu kux che
P (mg/kg)	25.77 (10.76)	12.98 (5.55)
C (%)	8.63 (2.75)	7.73 (1.60)
N (%)	0.71 (0.14)	0.73 (0.12)
C:N	12.08 (2.39)	10.58 (1.10)
Worms (per frame)	7.82 (8.00)	5.67 (4.57)
pH	5.88 (0.30)	5.91 (0.40)
Soil moisture (%)	89.82 (13.51)	91.63 (11.12)

Standard deviations in *parentheses*

Soil carbon did not change significantly with age or distance, but did show a significant interaction when considering the effect of age at each distance ($P = 0.0094$, $\alpha = 0.1$, Table 3). In younger trees, mean %C decreased with distance from *tao*, while in older trees, mean %C increased with distance from the study tree (Fig. 2). The effect of age is more pronounced on the inside, where differences between %C in the two age classes were greatest. Carbon appears to be accumulating most near the tree, earlier in its growth, and then decreases with age.

There was some evidence of an effect of age on C:N ratios ($P = 0.0608$). C:N ratios decreased from *mehen che* to *nu kux che* (12.08 in *mehen che* to 10.58 in *nu kux che*). There was also evidence that the effect of age on C:N ratios depends on distance ($P = 0.0735$, Fig. 3). The effect of age appears more pronounced inside the crown than at other distances (Table 3).

P values were high except for one case, comparison of young versus old C:N ratios at the Inside distance (in bold). C:N ratios inside the crown of *tao* was the only variable that showed a significant difference between younger and older trees. For P the mean for the Young group is higher than the Old group for each case of Inside, Edge, and Outside. The difference is statistically significant for Edge and Outside using the Tukey's test to control experiment-wise error.

Discussion

Tao was chosen for the study species because Lacandon farmers identified it as a tree fallow species

Table 2 Summary table of split plot analysis of Lacandon system, $\alpha = 0.1$

Source	df	*P values*						
		%N	%C	C:N	P	Worms	pH	%Soil moisture
Age	1	0.79	0.3392	**0.0608**	**0.0001**	0.2927	0.8194	0.6936
Distance	2	0.1583	0.2399	0.9487	**0.0767**	0.8650	**0.0028**	0.2650
Age * distance	2	0.2771	**0.0094**	**0.0735**	0.1217	0.7803	0.8394	**0.0216**
MSE(1)	16	0.049	14.857	8.672	65.90	42.35	0.220	335.58
MSE(2)	32	0.003	0.461	1.005	61.06	47.76	0.064	63.25

P values in *bold* indicate a statistically significant main effect or interaction. MSE(1) is the mean square error of the whole plot treatment factor (age) and MSE(2) is the mean square error used to test the subplot treatment factor (distance) and the interaction (age * distance)

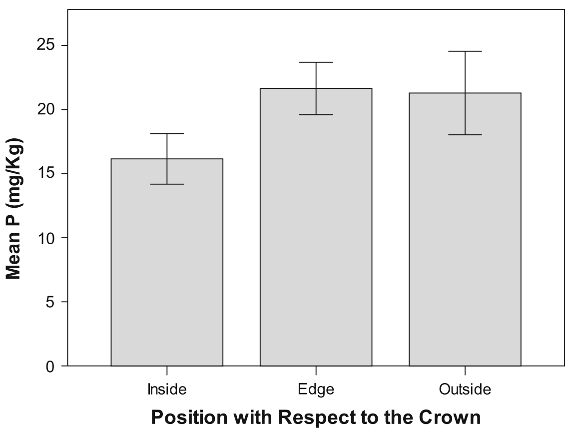

Fig. 1 Extractable soil phosphorus (P) inside the *tao* crown, at the crown edge, and outside the crown. *Error bars* are ±1 standard error

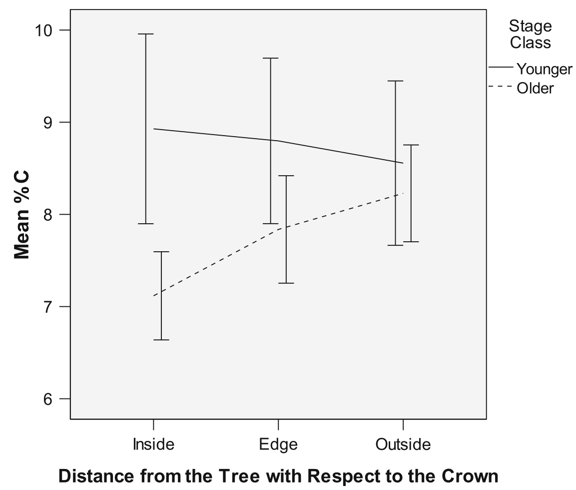

Fig. 2 Percent carbon (%C) in soil with age and distance from the *tao* tree. Younger refers to the *mehen che* stage, and older refers to the *nu kux che* stage. *Error bars* are ±1 standard error

Table 3 Comparisons of younger (mehen che) versus older (nu kux che) at each distance, inside, edge, and outside

Variable	Inside	Edge	Outside
C	−1.81 (0.56)	−0.96 (0.95)	−0.33 (0.99)
C:N	**−2.54 (0.07)**	−1.16 (0.78)	−1.15 (0.79)
Soil moisture	6.11 (0.90)	−7.00 (0.84)	6.89 (0.84)
P	−9.0 (0.18)	**−11.6 (0.04)**	**−19.6 (0.0001)**

The first number in the cell is the difference in means, the number in *parentheses* is the *P* value for the test of the null hypothesis of no difference between the population means of each group. The table shows only those variables where the interaction was significant so all differences represent "simple effect" comparisons (i.e., the difference between younger and older is examined at each level of the treatment factor "distance")

that enriches the soil (Diemont et al. 2006). Conventional metrics of soil fertility identified possibilities for this TEK. C:N ratios, for example, were low (Post et al. 1985), with a range of ~8 to 17. A decrease with age in C:N ratios indicates that the soil under *tao* may be enriching in nitrogen. Materials that have low C:N ratios decompose rapidly and release relatively larger quantities of nitrogen (Nair 1993). A lower C:N ratio indicates better litter quality, which is measured by how well the leaf litter breaks down. Litter quality under *tao* appears to be increasing with age. Saynes et al. (2005) found that soils from mid-successional forests (20–30 years after agriculture) had the highest C:N ratios. In contrast, the results indicate that soil under *tao* would lead to reduced C:N ratios over time. Later, in *nu kux che*, the leaf litter appears to be breaking down in such a way that nitrogen remains, relative to carbon. The C:N curve increases with distance in older trees and decreases in

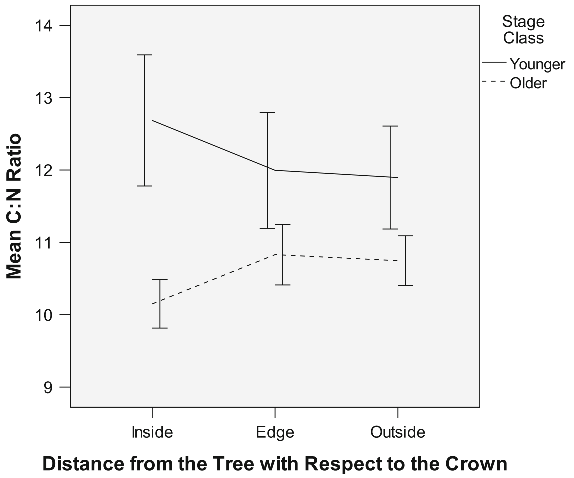

Fig. 3 Carbon to nitrogen (C:N) ratio in soil with age and distance from the *tao* tree. Younger refers to the *mehen che* stage, and older refers to the *nu kux che* stage. *Error bars* are ±1 standard error

younger trees. The trend in C:N suggests that the improved breakdown is a result of proximity to the tree stem. Nutrient losses in agricultural systems tend to be comparatively high (Sanchez 1987). Results for C:N indicate a retention of nitrogen in the soils under *tao*. C:N in older and younger *tao* are not changing uniformly with distance. The change in C:N ratio appears to be mostly determined by a reduction in carbon, as nitrogen remained relatively constant. The change in carbon appears to be the basis for the change in the C:N ratio. *Tao* appears to be enhancing the breakdown of leaf litter as the tree matures.

Although C:N ratios are decreasing with stage development, there was no effect of tree age or distance from the tree on %N in the soil. These results differed from findings by Diemont and Martin (2009), who found that total soil nitrogen increased with successional stage. Percent N values found in soils under *tao* were comparable to %N values of tropical soils studied by Martinelli et al. (1999), who concluded that N is relatively abundant in many tropical forest ecosystems. Percent N values ranged from 0.5 to 1.1%, which was somewhat higher than (Drew, unpublished data) found in the volcanic soils of Dominica. A study of soil C and N dynamics in primary and secondary seasonally dry tropical forests previously under agriculture in Mexico (Saynes et al. 2005) revealed that early (10–15 years after cultivation) and mid-successional (20–30 years after cultivation) forests had the highest total and mineral N pools and potential N transformations, whereas the lowest N pools and potential cycling were found in primary forests.

Percent carbon increased with distance in older trees. These results indicate that organic matter increases with distance from *tao* in older fallows. There is potentially a faster breakdown of litter within the *tao* canopy by soil macrofauna, although no significant trends in earthworms were found to support this claim. Peñuela and Drew (2004) found erratic results regarding worm density in their study of restored abandoned pasture in Costa Rica. They reasoned that the 7-cm sampling depth (equivalent to our sampling depth) may have been too shallow for accurate worm estimation. In their study of all six phases of Lacandon soil ecology, Diemont and Martin (2009) found that soil organic matter increased with each successional stage following intentional burn, nearly doubling 40 years later. Slightly different results were recorded by Saynes et al. (2005); litter production was higher in early and mid-successional forests than in late-successional and primary forests. Palm (1995) claims that the quantity of soil organic matter is not as important to soil fertility as its structure and composition.

Soils around *tao* appear to be losing extractable phosphorus as the tree matures. Reduced phosphorus in the soil indicates an increased phosphorus demand in older *tao*. The increased demand does not appear to come at the expense of *tao*, which may be more important in older fallows than younger fallows (77.4% in older fallows compared to 60.18% in younger fallows) (Cheng 2009). It is possible that *tao* generally has a high phosphorus demand, as the increase in P with distance from *tao* in younger fallows supports. Diemont and Martin (2009) found P concentrations to be higher in *jurup che* than *mehen che* or *nu kux che*. In the *jurup che*, they found elevated P concentrations in the presence of woody plants, raising the possibility that these plants are pioneering nutrient-rich areas (Siemanns and Rogers 2003). Binkley and Giardina (1998) propose that a successful strategy for a tree species on a high nutrient site might be to reduce the supply of the nutrient for competitors. It is therefore possible that an increased uptake of phosphorus by *tao* insures its abundance in the forest fallow. Diemont et al. (2006) found evidence that *S. lateriflorum* was retrieving P from the subsoil. P increased with size of *S. lateriflorum* ($P = 0.04$). The decreased P in soils around *tao* possibly corresponds with increased phosphorus in *tao* biomass, a possibility that should be further investigated. *Tao*'s contribution of P to the soil is likely largely realized at the time of burn, when nutrients locked in the biomass return to the soil.

This study examined one example of traditional ecological knowledge (TEK) focusing on a tree fallow species that was valued by farmers for fallow regeneration. *Tao* may be enhancing soil fertility through improvement of litter quality as seen in reduced C:N ratios near the stem of older trees. Future work should examine the role that seasonality plays in nutrient dynamics. This work contributes to a larger body of work on TEK that attempts to bridge the gap between traditional knowledge and western science.

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