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Chapter 9

EFFECTS OF MANAGEMENT PRACTICES ON COFFEE PRODUCTIVITY AND HERBACEOUS SPECIES DIVERSITY IN AGROFORESTRY SYSTEMS IN COSTA RICA

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ABSTRACT

Agroforestry systems (AFS) have the potential to provide socio-economic benefits and also environmental services such as biodiversity conservation. In agricultural ecosystems like AFS, plant productivity is largely dependent on the type and intensity of management. Management practices like fertilization, pruning, thinning, mulching, and certain associations between crops and shade tree species have a strong influence on plant productivity and therefore on crop yields; likewise management practices have an effect on the biodiversity that occurs in AFS. This chapter addresses the question of how to manage AFS to increase or maintain agricultural productivity while conserving biodiversity. We describe the effects of alternative management practices on coffee yield and on the herbaceous species richness of an experimental coffee AFS established in Turrialba, Costa Rica in 2000-2001. The AFS experimental design was an incomplete factorial design with three repetitions. It consisted of shaded coffee (*Coffea arabica* var caturra) plots with three native tree species alone and in combination: *Terminalia amazonia*, *Erythrina poeppigiana*, and *Chloroleucon eurycyclum*. The experimental

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design also included plots of non-shaded coffee monoculture. The agroforestry plots were managed with either organic or chemical nutrient inputs at two intensity levels. We quantified herbaceous plant diversity and recorded coffee productivity (bean yield) across all combinations of shade tree species and management practices. Our results indicated that: 1. Intermediate management intensity produces competitive coffee yields. 2. Organically managed plots have high herbaceous diversity and can be as productive as chemically managed plots. 3. Shaded coffee AFS can be almost as productive as non-shaded, monoculture coffee farming systems. These results suggest that it is feasible to manage these AFS for agricultural productivity while maintaining uniform soil cover and a significant number of herbaceous species.

INTRODUCTION

The conservation of biodiversity in transformed or degraded landscapes is an active research area (Schroth et al. 2004). The effectiveness of alternative strategies for the preservation of biodiversity is limited by our knowledge of the mechanisms that maintain diversity and the linkages between diversity and ecosystem processes (Tilman 2000). Numerous studies on temperate grasslands, large-scale cross-country projects and controlled laboratory experiments have shown that biodiversity can have strong effects on plant productivity and on other ecosystem processes (Tilman et al. 1997; Hector et al. 1999; Naeem et al. 2000; Loreau et al. 2001; Tilman et al. 2001). In managed ecosystems biodiversity seems to be inversely related to management intensity (De Fries et al. 2004). It is important to determine how biodiversity loss in managed ecosystems will affect the flow of goods and services that society derives from these ecosystems (Solé and Bascompte 2006).

Agroforestry systems (AFS) have the potential to be productive while conserving a portion of the biodiversity that occurs in natural ecosystems (Garrity 2004). Agroforestry can balance the tradeoffs between farmers' economic needs, ecosystem services and biodiversity conservation (Steffan-Dewenter et al. 2006). AFS provide a refuge for biodiversity, can supply other environmental services, and are suitable for agro-ecological research (Ashton and Montagnini 1999; Bhagwat et al. 2008; Perfecto et al. 1996).

Different management practices and shade tree species can have contrasting effects on AFS productivity and on associated biodiversity (Nair 1993). In agroforestry experiments plant species diversity, species composition and management practices can be manipulated or adjusted at a relatively low cost (Nair 1993; Peeters et al. 2003). Such experiments can advance our understanding of the effects of different management regimes on agricultural productivity, biodiversity and other ecosystem processes in managed ecosystems (Hooper et al. 2005; Perfecto et al. 2005).

Coffee, *Coffea arabica* L. (Rubiaceae) is a major crop and an important income source for farmers in Central and South America. It is one of the world's most important agricultural commodities and provides economic support for 20 to 25 million people (http://faostat.fao.org; Aguilar and Klocker 2000; Schroth et al. 2004). There are several advantages in growing coffee in AFS in comparison with intensive monocultures. For example, it has been shown that coffee AFS have higher nutrient retention than intensive systems (Imbach et al. 1989). In addition, in coffee AFS shade improves coffee bean quality (Muschler 2001). Coffee AFS also require less agrochemical inputs (Young 2003) and can maintain soil fertility for longer periods of time (Siebert 2002).

Market fluctuations, price speculation, and unfair trade have recently led many coffee farmers to develop new management practices, experiment with organic inputs, or switch to other crops (Fernández and Muschler 1999, Haggar et al. 2001). Rising environmental and health concerns have promoted the interest in organic production systems and their environmental services (Rice and Ward 1996). Organically grown coffee can be as productive as conventional unshaded systems (Lyngbaek et al. 2001). To explore these claims further, a research team at the Tropical Agriculture Research and Higher Education Center (CATIE) of Costa Rica established an experiment in 2000-2001 to describe the effects of different management practices and shade tree species on the productivity and sustainability of coffee AFS (Beer et al. 1998; Haggar et al. 2001; Haggar 2005). These AFS included different management practices (with chemical and organic inputs) and three native shade tree species.

The diversity of herbaceous species growing in the understory of an AFS can serve as an indicator of the effects of different management practices on plant diversity. Understory plants are directly influenced by management practices including fertilization, weed control, mulching and shade. The amount of light that reaches the understory, the availability of nutrients in the upper layers of the soil and the physical structure of the soil also affect the growth of understory plants.

This chapter describes the effects of management practices (chemical and organic), at different intensity levels on understory herbaceous species diversity and coffee productivity after six years of monitoring. We hypothesize that it is possible to obtain competitive coffee bean yields while conserving herbaceous species diversity.

METHODS

Site Description

The study was conducted at an experimental coffee agroforestry system located at the Tropical Agriculture Research and Higher Education Center (CATIE) in Turrialba, Costa Rica (9°53´44´´ N; 83°40´7´´ W). The site is located at 685 m above sea level, the rainfall averages 2600 mm/year with a dry season of 1-2 months, and the average temperature is 21.8°C, with 88% humidity and a solar incidence of 16.9 Mj/m² (Zuluaga Peláes 2004). The coffee agroforestry system (AFS) is located at CATIE'S experimental and commercial farm. The AFS is surrounded by sugar cane (*Saccharum officinarum* L.) plantations, a few scattered native trees, and pasture lands. The area had been planted with sugar cane for at least five years before the establishment of the experiment.

The soils are Typic Endoaquults (Ultisols) derived from volcanic alluvium. They are shallow, rocky and acidic (pH < 5.5), with high clay content (clay > 50%). The soils had low to medium organic matter content at the time of establishment of the experiment. The soil chemical properties were consistent across the site. The most severe soil limitation was the poor drainage; several ditches were built across the site to improve drainage. To reduce acidity, calcium carbonate was applied between the coffee alleys during the first two years.

Agroforestry System Design and Shade Tree Species

The *Coffea arabica* var Caturra AFS was established in 2000-2001. The experiment had a total size of 9.2 hectares. Coffee planting density was 5000 coffee shrubs ha^{-1}; with 2 m between rows and 1 m between coffee shrubs, which is the standard planting density for coffee in Costa Rica. The experimental treatments were defined as the combination of shade type and management practices. Treatments were comprised of combinations of three management interventions: organic or chemical management, input intensity (quantity of inputs per area), and shade tree species. Not all combinations were tested, resulting in an experiment with 20 different treatments, each with three replicates (Table 1).

Table 1. Coffee AFS: The experiment has an incomplete factorial design; the combination of the shade type and the management practices constitutes the treatment. There were 20 treatments with 3 replicates each

Shade tree species	Management type	Management intensity
Erythrina poeppigiana	Chemical inputs	High intensity
		Medium intensity
	Organic inputs	Medium intensity
		Low intensity
Terminalia amazonia	Chemical inputs	High intensity
		Medium intensity
	Organic inputs	Medium intensity
		Low intensity
Chloroleucon eurycyclum	Chemical inputs	Medium intensity
	Organic inputs	Medium intensity
T. amazonia + *C. eurycyclum*	Chemical inputs	Medium intensity
	Organic inputs	Medium intensity
T. amazonia + *E. poeppigiana*	Chemical inputs	Medium intensity
	Organic inputs	Medium intensity
C. eurycyclum + *E. poeppigiana*	Chemical inputs	High intensity
		Medium intensity
	Organic inputs	Medium intensity
		Low intensity
Full sun (no shade)	Chemical inputs	High intensity
		Medium intensity

Three shade tree species were used in the AFS: *Chloroleucon eurycyclum* Barneby and J.W. Grimes (Fabaceae) (this species is also reported in the literature as *Abarema idiopoda*); *Terminalia amazonia* (J.F. Gmel.) Exell (Combretaceae) and *Erythrina poeppigiana* (Walp.) O.F. Cook (Fabaceae). *C. eurycyclum* is a slow-growing, nitrogen-fixing timber tree species; there is little information on its productivity in AFS (Cordero et al. 2003). *T. amazonia* is a fast-growing timber species. It is widely distributed and cultivated across Latin America and is highly adaptable to numerous soil conditions (Montero and Kanninen 2005; Montagnini et al. 2008; Piotto et al. 2010). *E. poeppigiana* is a nitrogen-fixing species, commonly used in Costa Rica in several types of AFS (Beer et al. 1998). Shade trees were planted in alternate rows at 6 m x 4 m with an initial shade tree density of 417 trees ha^{-1}, and they were thinned 4 years after planting. In 2008, when the present study was conducted, the tree density had been reduced by 40%. *E. poeppigiana* trees were pollarded according to conventional coffee AFS management practices to add organic matter to the soil. *C. eurycyclum* and *T. amazonia* were pruned to promote straight stem growth. No genetic selection or progeny tests have been done with the selected tree species, therefore available planting materials displayed high genetic variability (Galloway and Beer 1997).

Coffee Management Practices

Two different kinds of management practices were used in the coffee AFS: chemical (also referred to as conventional) and organic (Lyngbaek et al. 2001). Conventional chemical management was based on agronomic recommendations of the Costa Rica Coffee Institute, and included the use of chemical fertilizers, fungicides and pesticides at two intensity levels: high (800 kg ha^{-1} yr^{-1} of chemical input) and medium (400 kg ha^{-1} yr^{-1}). These practices are commonly used in unshaded coffee systems as well as in coffee AFS with a single shade tree species (Sanchez-De León et al. 2006).

In plots with organic management chicken manure and organic matter (coffee pulp) were used at two intensity levels: medium and low. The medium intensity level consisted of 20 tons $ha^{-1}yr^{-1}$ of coffee pulp, 7.5 tons $ha^{-1}yr^{-1}$ of chicken manure, 200 kg $ha^{-1}yr^{-1}$ of a potassium-magnesium-sulfate mixture (KMAG), and 200 kg $ha^{-1}yr^{-1}$ of phosphate mineral. The low intensity level consisted of 10 tons $ha^{-1}yr^{-1}$ of coffee pulp, chicken manure and phosphate mineral (Sanchez-De León et al. 2006). Pests were controlled by removing infected fruits and by selective pruning. A committee of local coffee farmers and agronomists revised and approved the chosen management procedures. These practices represent local knowledge and aim to become agronomically and economically feasible alternatives for small farmers (Sanchez-De León et al. 2006).

Understory Species Richness, Composition and Abundance

To estimate the understory plant diversity a detailed survey of herbaceous vegetation in the AFS was conducted. Preliminary field observations and local sources indicated that herbaceous species richness and cover were homogeneous within treatments. In each treatment/plot a 4 m x 4 m subplot was located randomly. Within each subplot all plant individuals were identified and counted to estimate understory species richness and abundance. The herbs were identified to species level with the aid of local and regional floras, photographic databases, and online herbarium databases. When reliable identification to the species level was not possible, the individuals were classified as morpho-species. The herbaceous species that displayed colonial growth form (asexual reproduction) and the grasses that could not be identified as individuals were recorded by measuring the size of the covered area in meters. The area of litter, bare soil and herbaceous cover in each $16m^2$ subplot were measured using a one meter square frame.

Coffee Productivity Evaluation

The coffee yield data were obtained from harvest records. For each treatment plot, the weight of the total coffee berry harvest was recorded every year. Total averages per treatment were obtained from the three replicates of each treatment. Yield data were compared on a per-area and per-plant basis to correct for potential differences in plot sizes. These measures were used to compare the yield data across treatments.

Data Analysis

To describe the effects of management practices on coffee bean productivity and on herbaceous species diversity in the AFS we used the repeated measures ANOVA procedure with a general linear model in SAS. We sought to compare differences in coffee yield across treatments, differences in understory plant richness across treatments, and to determine how coffee bean yields were changing in time. We used dynamic tables in Excel to compare yields across treatments, years, management practices, and shade types.

RESULTS

Herbaceous Species Richness, Abundance and Soil Cover

Our results indicated that management practices had a strong effect on herbaceous species richness. Herbaceous species richness was consistently lower under high intensity chemical treatments regardless of shade tree species (Figure 1).

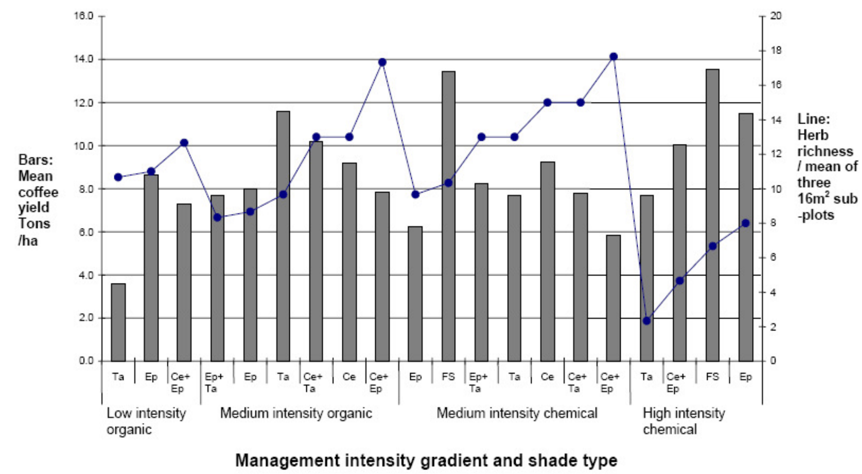

Figure 1. Herb diversity and coffee productivity along the management intensification gradient (data from 2007). Grey bars correspond to coffee yield and are arranged by management practices (from low-intensity organic to high-intensity chemical) and by shade type. The shade tree species are: Ta-*Terminalia amazonia*; Ce-*Chloroleucon eurycyclum*; Ep-*Erythrina poeppigiana*; the four letters correspond to shade tree species combinations and FS to full sun grown coffee. The dots correspond to the mean herb species richness per three $16m^2$ sub-plots for each treatment. The dots were displayed in a continuous line to show how the relationship between herb species richness with management practices.

The high intensity chemically managed plot (CH) with *T. amazonia* presented the lowest herb richness (2 species-mean of three $16m^2$ plots) of the AFS. The full sun treatments (FS) also had low herbaceous species richness. The herbaceous ground cover was consistently higher in organic treatments (OL, OM) followed by CM treatments.

The plots managed with medium intensity (Chemical Medium-CM and Organic Medium-OM) displayed the highest herbaceous species richness with up to 18 species (mean of three $16m^2$ plots) in CM and OM with both *E. poeppigiana* and *C. eurycyclum* (Figure 1). The CM and OM treatments with *C. eurycyclum* also had consistently high species richness values. Both CM and OM treatments also had high variability in species richness.

Regarding the influence of shade tree species, treatments with *C. eurycyclum* had the highest herbaceous species abundance, high herbaceous species richness and a very small area of exposed soil (Table 2). The treatments with both *C. eurycyclum* and *E. poeppigiana* had high or intermediate values of herb and litter soil cover and also small areas of exposed soil.

The treatments shaded with *E. poeppigiana* had high litter production. The unshaded (FS) treatments had the highest total area of bare soil; almost no herb species grew under the high intensity, full sun management practices.

Over 90% of the herbaceous species sampled were identified to species; the Poaceae (grasses) and the Cyperaceae (sedges) were the most abundant families in the coffee AFS. Grasses were highly abundant in FS treatments (Table 3) and under conditions of FS and high chemical fertilization. The abundance of Cyperaceae and the observations in the field confirmed that limited drainage on this site favors water tolerant species in the Cyperaceae and Caryophillaceae families. Seedlings and saplings of coffee, *E. poeppigiana* and *A. idiopoda* were also abundant across plots. *Borreria* sp (Rubiaceae), *Drymaria* sp (Caryophyllaceae) and especially *Hydrocotile* sp (Apiaceae) provided uniform and, in some plots, extensive soil cover.

Coffee Yields

Overall, the high intensity chemical treatments (CH) displayed considerable variation in productivity between treatments, shade type and years. In 2007 the highest yield was recorded in full sun (FS) chemical high input (CH) plots with yield over 13 Mg/ha.

Table 2. Coffee AFS soil cover: herb richness (S), herb abundance and % area by cover types. Mean and +/- square error of the mean (SEM) from three 16m^2 plots per treatment

Shade tree species	Management	Mean richness (#species)	Species richness (SEM)	Mean abundance (indiv/ plot)	Abund. (SEM)	Plot herb cover (%)	Plot litter cover (%)	Bare soil area (%)
Ce	Med. Chem.	15	3.46	109.67	42.74	45.7	32.0	16.3
Ce	Med. Organic	13	6	56	43.09	77.5	14.2	0.0
Ce + Ep	High Chem.	4.7	0.58	72.33	108.89	9.4	56.3	31.3
Ce + Ep	Low Organic	17.7	1.53	71.33	57.87	68.0	20.7	5.9
Ce + Ep	Med. Chem.	17.3	2.31	46.33	1.53	39.3	37.3	14.6
Ce + Ep	Med. Organic	12.7	1.15	25.33	4.04	79.2	7.3	1.1
Ce + Ta	Med. Chem.	15	1.73	34.17	2.57	11.6	55.2	32.1
Ce + Ta	Med. Organic	13	2	29.67	15.31	77.7	17.1	1.6
Ep	High Chem.	8	3.24	70.25	11.21	11.4	88.2	0.0
Ep	Low Organic	9.7	5.51	22.67	17.62	60.2	35.4	0.0
Ep	Med. Chem.	8.7	5.13	37	23.64	16.3	76.1	3.1
Ep	Med. Organic	11	1	32.67	17.39	51.7	37.9	0.0
Ep + Ta	Med. Chem.	13	2.65	49.33	7.09	14.1	65.4	13.1
Ep + Ta	Med. Organic	8.3	1.15	21.33	13.65	71.9	12.5	7.9
Ta	High Chem.	2.3	1.53	85.67	39.37	2.3	92.7	2.1
Ta	Low Organic	13	3	53.33	20.82	85.3	10.9	3.6
Ta	Med. Chem.	9.7	2.08	48.33	41.53	17.2	66.5	15.8
Ta	Med. Organic	10.7	3.79	30.67	5.77	80.8	9.4	0.0
FS	High Chem.	6.7	1.86	52.67	33.95	17.8	49.6	28.8
FS	Med. Chem.	10.3	6.03	21	16.52	52.1	25.0	15.6

Table 3. Most common species and number of occurrences in the 4 x 4 m sampling plots

Family	Species	Occurrences	Taxonomic summary
Caryophyllaceae	*Drymaria cordata*	30	Number of plant families recorded in the experiment: 27
Poaceae	*Paspalum conjugatum*	30	Number of herb genera recorded in the experiment: 50
Rubiaceae	*Coffea arabica* (saplings)	30	Total Number of herb species: 58
Apiaceae	*Spananthe paniculata*	27	
Poaceae	*Digitatia sanguinalis*	27	Most abundant herb families
Poaceae	*Paspalum conjugatum*	27	Cyperaceae (sedges): 8 species
Apiaceae	*Hydrocotyle umbellata*	26	Poaceae (grasses): 6 species
Rubiaceae	*Borreria laevis*	26	
Cyperaceae	*Cyperus tenuis*	24	Most common genus: Cyperus
Euphorbiaceae	*Phyllantus niruri*	24	
Cyperaceae	*Cyperus luzulae*	23	
Cyperaceae	*Cyperus tenuis*	23	
Leg-Mimosaceae	*Mimosa pudica*	22	
Cyperaceae	*Dichromena ciliata*	21	
Leg-Fabaceae	*Erythrina poeppigiana* (saplings)	21	
Asteraceae	*Pseudoelephantopus spicatus*	20	

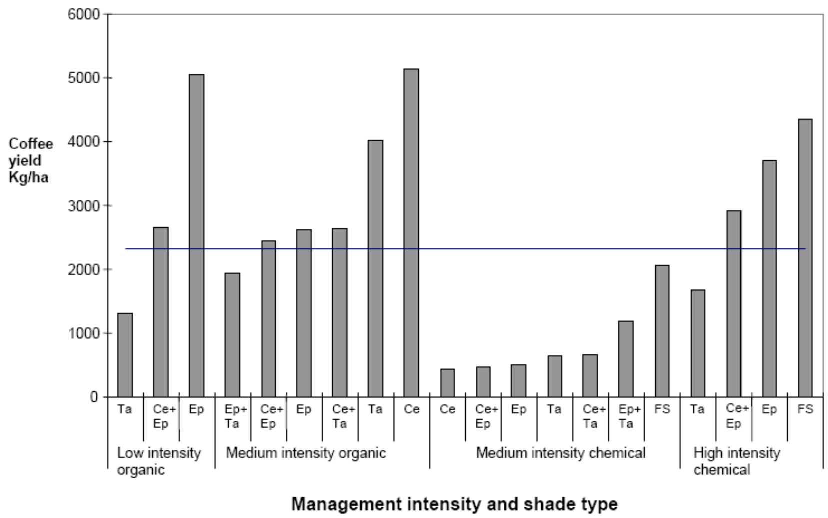

Figure 2. Coffee AFS mean bean yields for 2006. The bars show the yield per plots arranged by management practices (low intensity organic to high intensity chemical) and by shade type. The line corresponds to the 2006 mean coffee bean yield across all treatments.

Plots with *E. poeppigiana* and the combinations of *E. poeppigiana* and *Chloroleucon eurycyclum* produced the highest yields after the full sun CH treatment (Figure 1-3). Plots shaded with the timber tree *Terminalia amazonia* tended to have lower coffee yields with the exception of one OM plot.

In contrast, at intermediate management levels (CM, OM) the yields displayed less variation between years and shade types (Figure 1-3). The comparison between chemical medium and organic medium treatments showed that at intermediate management levels the total yields were very similar, regardless of shade tree species, or input type. Furthermore, in 2007, with the exception of full sun CM treatments, medium organic treatments had the highest total yield. The low intensity organic treatments (OL) had the lowest coffee yields.

Because coffee presents a biannual fruiting pattern we show the results of the last two years on record, 2006-2007 (Figures 1-2); this biannual pattern is a physiological trait of the coffee shrub and is largely independent of the site conditions. The year 2007 was a high yield year (Figure 1) and 2006 was a low yield year (Figure 2). Our ANOVA showed a very strong effect of time on productivity (Table 4), this effect was probably caused by the year-to-year evolution of the AFS and the gradual increase in yields as the coffee shrubs matured (Figure 3). We also observed a small positive effect of understory diversity on coffee yield (Table 4). These yield data indicate that the AFS productivity has been increasing gradually over the last 6 years and that there is a significant effect of management on productivity as can be seen in Figures 1 and 2.

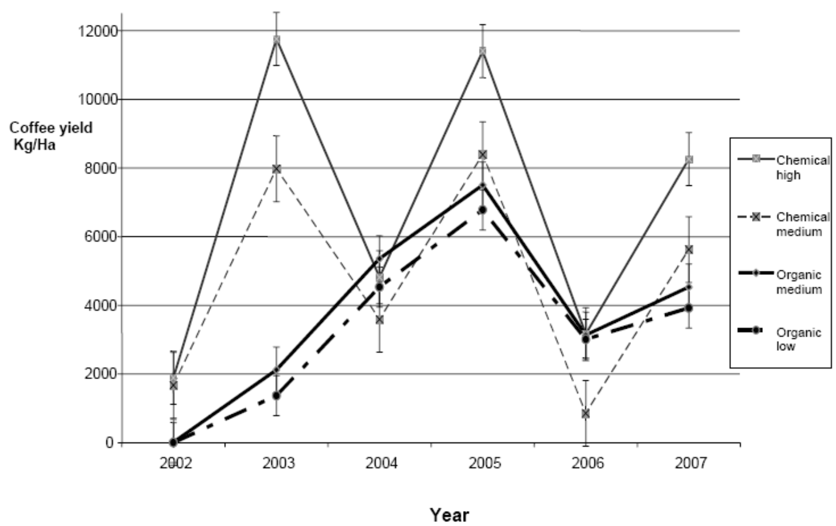

Figure 3. Historical mean yields of the coffee AFS grouped by management practices for 2002-2007. Organic treatments (black thick lines) display smaller inter-year oscillations than chemical treatments.

Table 4. Time, management and herb richness effects on coffee yield

Source of variation	Pr > F
Time	<.0001
time * management	<.0001
time * herb richness	0.0020
time * herb richness * management	0.0044
time * block	0.9299

Chemically managed plots at high and medium intensity levels were highly productive by the second harvest (2003) and displayed considerable variation in inter-year yield. Interestingly, in organically managed plots mean yield increased slowly (with low productivity in 2002 and 2003) but displayed smaller inter-year variation. In the years 2004 and 2006 organic treatments were as productive, or in some cases, more productive than chemical treatments (Figure 3).

The productivity of the system in 2006 indicates that in low yield years, the CM plots tend to perform poorly, especially the full sun plots (mean yield for the full sun CH was 4.2 Mg/ha in 2006 and 13.5 Mg/ha in 2007). In contrast, organically managed plots have higher yields than chemically managed plots during low yield years; in 2006 medium intensity organic treatments were significantly more productive than medium intensity chemical (CM) plots (Figure 3). Also the year-to-year yield variability was higher for CH than for the CM plots (Figure 3).

DISCUSSION

Impact of Management Intensity on Coffee Yield and on Herbaceous Species Diversity

In general, understory herbaceous species diversity was positively correlated with coffee yield, the only exceptions were the intensive treatments – especially the unshaded, high intensity chemically managed treatments. This suggests that coffee productivity and herbaceous species richness can be maintained simultaneously in coffee AFS, especially at intermediate levels of management intensity.

Also, it could be argued that biodiversity can have a small positive effect on productivity, as shown by Figures 1-2. Given that some management practices like the pollarding of *E. poeppigiana* tended to have negative impacts on herbaceous growth it is interesting that a small biodiversity effect could still be detected.

It is possible that in these AFS herbaceous diversity influences coffee productivity in an indirect manner: for example, herbaceous cover could be contributing to erosion control, addition of organic matter to the soil, and enhanced nutrient cycling (Altieri 1999; Smith et al. 2008; Vandermeer 1989).

Other studies have reported that as management intensity increases, biodiversity tends to decrease (DeFries et al. 2004). Our results indicated that a sharp decline in herbaceous species richness was associated with chemically intensive management practices, while medium intensity treatments (CM and OM) produced similar coffee yields; therefore medium-intensity management practices may represent a reasonable balance between coffee productivity and biodiversity conservation for farmers in Costa Rica.

Our data indicated that as in other agricultural systems in the region the Poaceae (grasses) were very abundant (Table 3). While some species of Poaceae can benefit commercial crops and livestock, most grass species are considered undesirable in coffee AFS. In the full sun AFS treatments, controlling undesirable grasses commonly required the use of chemical herbicides; while in shaded plots undesirable species were less frequent (Romero, pers. com).

Whether the optimal management practices for coffee AFS should be totally organic, chemical or a mixture of the two would depend on the availability and use of organic and chemical inputs, the management objectives and the preferences of the land manager. It is likely that as organic technologies advance, the quality of organic inputs will improve. In some tropical regions small farmers can easily produce their own high quality organic inputs. Improved organic technology has the potential to increase the profitability of these agroforestry systems. For example, in the Turrialba area of Costa Rica, organic coffee farmers receive higher prices for their coffee than conventional farmers. This price premium constitutes an incentive for improved management practices but sometimes is not enough to cover certification and other costs associated with organic production (Muschler 2001).

Influence of Shade Tree Species

We observed that the shade tree species *C. eurycyclum* apparently had a positive effect on herb species richness and on coffee productivity. Its relatively open canopy allows some light to reach the understory, making it a potentially desirable tree species for AFS (Figure 4); also, preliminary observations suggest that *C. eurycyclum* has root nodules and therefore could be actively fixing nitrogen. However, the *C. eurycyclum* in the AFS had poor form and shape and probably lacked quality for saw timber. Local farmers reported that the high density of the wood made pruning difficult. *Chloroleucon eurycyclum* is a promising shade tree species, however more research and genetic selection is needed to obtain more benefits from its association with coffee in AFS.

Figure 4. Coffee agroforestry system shaded with *Chloroleucon euryclyclum*.

The treatments with *Erythrina poeppigiana* confirmed the benefits of the use of this well-known shade tree species in Costa Rica (Beer et al. 1998). Although the treatments shaded with *E. poeppigiana* were productive, the herbaceous species richness under *E. poeppigiana* was low, probably because the abundant tree mulch suppressed the herbs in the understory. In combined plots with *E. poeppigiana* and *C. eurycyclum* the overall herb richness was much higher than in the treatments with *E. poeppigiana* shade alone (Figure 5).

The treatments shaded with *Terminalia amazonia* (Figure 6) presented low herbaceous species richness and intermediate coffee yields. This species of relatively valuable timber could probably be managed for timber and shade in combination with other species. Overall, the combination of shade tree species probably provides farmers with more benefits: *C. eurycyclum* provides intermediate shade and organic matter to the soil, *T. amazonia* produces straight, high quality timber and *E. poeppigiana* produces mulch and can be pruned easily to adjust light conditions to the needs of the coffee shrubs (Figure 7).

Figure 5. Coffee agroforestry system with pruned *Erythrina poeppigiana*.

Figure 6. Coffee agroforestry system shaded with *Terminalia amazonia.*

Figure 7. Coffee agroforestry system with *Erythrina poeppigiana* and in the back *Chloroleucon eurycyclum*.

Long Term Sustainability of Coffee AFS

The full sun CH treatments had highly variable yields from year to year and had very low herbaceous species richness. These unshaded CH treatments can also have high erosion rates depending on the slope and soil type (Rice 1991). Often, due to the costs of chemical inputs these intensive systems are not suitable for small farmers.

The coffee yield year to year records suggest that the AFS is maturing and that yields are increasing with time. The organic treatments seem to be slowly attaining productivity levels similar to those of chemical treatments. In addition, coffee yields were less variable year to year in the organic than in the conventional system.

This could indicate that organic treatments can have positive effects on the nutrient cycles in these AFS. As the system matures and soil processes continue, bean yields and biodiversity can increase and year to year variations can decrease. Overall, these trends suggest that these coffee AFS can be more sustainable than intensive coffee monocultures.

CONCLUSION

This study shows that coffee AFS can be managed for competitive coffee yields while maintaining herbaceous species diversity. Our data showed that low intensity management tended to produce poor yields, while high intensity management has low diversity and can be expensive. Thus, an optimal agroforestry management strategy for coffee productivity and biodiversity can probably be attained using organic inputs at intermediate intensity and complementing them with chemical inputs if needed. The data also demonstrated that as the organic AFS mature they become more productive and probably more resilient.

The comparisons of different shade tree species confirmed the benefits of *Erythrina poeppigiana* in coffee AFS. *Chloroleucon eurycyclum* had positive impacts on diversity and coffee productivity and could be successfully combined with other species to provide shade in AFS.

The adaptability of the timber species *Terminalia amazonia* makes it a useful tree species for coffee AFS. *Terminalia amazonia* benefits can probably be maximized if it is planted in combination with other shade tree species that can contribute with nitrogen fixation such as *C. eurycyclum* and *E. poeppigiana*.

This management strategy, combination of timber and nitrogen fixing species in organic coffee AFS can be easily transferred to farmers in Costa Rica and other countries in Central America.

This is especially relevant in regions where farmers have poor access to chemical inputs and can benefit by selling organically produced coffee. In addition, the organic systems can promote restoration and conservation of biodiversity.

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