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Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America

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Abstract

During most of its cultivation in Central America, coffee (*Coffea arabica* L.) suffered few serious pest problems. However, over the past three decades, three factors contributed to significantly increase pest levels and losses: the recent introduction of new pests; more favorable conditions for existing pests, diseases, and weeds due to lower shade levels; and secondary pest problems caused by pesticide use. The strategy of maximizing coffee production with pest control dominated by synthetic pesticides has not only increased yields substantially, but also production costs, pesticide resistance, and both human health and environmental risks. An analysis of the response of the food web in coffee plantations to varying levels of light and humidity associated with different shade levels provides the basis for identifying the optimum shade conditions which minimize the entire pest complex and maximize the effects of beneficial microflora and fauna acting against it. These optimum shade conditions for pest suppression differ with climate, altitude, and soils. The selection of tree species and associations, density and spatial arrangement, as well as shade management regimes are critical decisions for shade strata design. Site-specific knowledge of the seasonal food web dynamics permits growers to determine the appropriate seasonal shade management in order to further suppress pest levels. For example in a low-elevation dry coffee zone, 35 to 65% shade promotes leaf retention in the dry season and reduces *Cercospora coffeicola*, weeds, and *Planococcus citri*; at the same time, it increases the effectiveness of microbial and parasitic organisms without contributing to increased *Hemileia vastatrix* levels or reducing yields. In these conditions, shade should be at a maximum early in the dry season and at a minimum by the middle of the rainy season. Further research is needed on: the effects of individual tree species on the food web; the role of canopy architecture for coffee vigor, photosynthesis, leaf drying, pest susceptibility, and pruning regimes; and on simple observation methods and decision criteria for farmer management of tree-coffee-food web interactions.

Introduction

During most of the 200 years that coffee (*Coffea arabica* L.) has been cultivated in Central America, it suffered few serious pest problems. Coffee pests such as leaf rust (*Hemileia vastatrix*) and berry borer (*Hypothenemus hampeii*) have reached the New World only recently. Furthermore, the usually shaded environment of coffee plantations kept existing pests below excessive levels or facilitated their control. For example, the coffee leaf miner (*Leucoptera coffeella*) was present in coffee fields without causing significant damage. Weeds were controlled in shaded coffee with infrequent slashing. An exception was American leaf spot (*Mycena citricolor*), a New World coffee disease which flourishes under higher humidity, a condition accentuated by shade.

Consequently, in high-humidity environments, shade levels were often kept at a minimum.

Over the past three decades, pest levels and losses due to pests (including diseases) have increased substantially. There are three main reasons for this. First, in the past three decades two important coffee pests have reached and spread throughout Central America. The coffee berry borer appeared in Guatemala in 1971 and is now widely distributed with the exception of Panama (Dufour et al., 1999); its establishment in Costa Rica was officially recognized in 2000. Similarly, coffee leaf rust first appeared in Nicaragua in 1976 and spread throughout the region by 1983 (Avelino et al., 1999).

Second, the intensification of coffee production based on external inputs of synthetic chemicals and the promotion of coffee varieties with higher yield potential in full sun fomented the reduction of shade levels, thus creating favorable conditions for numerous pests which were previously uncommon in shaded coffee; the controversial claim of higher incidence of coffee leaf rust under shade contributed to this tendency. As a consequence, brown eye spot disease (C*ercospora coffeicola*) has proliferated in open-sun coffee, despite the use of fungicides (Samayoa and Sanchez, 2000); simultaneously, weed growth and herbicide use have also increased with reduced shade levels (Fernandez and Muschler, 1999). Another effect of reducing the shade is reduced organic matter inputs and, hence, declining soil organic matter (SOM). This, in turn, has been linked to increased nematode damage which may be particularly accentuated on the often smaller and less vigorous root systems of the shorter-statured coffee varieties (Villain et al., 1999). The overall result is that, in high-input modern coffee production systems, growers often use herbicides, fungicides, nematicides and insecticides in a single season.

Third, the intensive use of pesticides has created secondary pest problems due to organisms normally present, but previously not economically damaging. These secondary pest problems often arise as a side effect of pesticide use. For example, insecticide use to control the leaf miner in sun-exposed coffee fields reduced the natural enemies of mealybugs (*Planococcus citri*). Although generally uncommon as pests, mealybugs can devastate entire flower clusters and cause up to 50% yield reductions (J. Monterrey, pers. comm., 2000). In another example, the drift from contact herbicides can produce virtually invisible micro-lesions on lower coffee leaves, which become entry sites for anthracnose (*Colletotrichum* spp.), an opportunistic fungus that contributes to coffee branch dieback (Monterroso, 2000).

The strategy of maximizing coffee production, typically by using synthetic fertilizers and agrochemicals, has not only increased yields substantially, but also production costs, pest resistance (Brun et al., 1989; Njoroge, 1991), secondary pests (Monterrey, 1991; Llana et al., 1992; Guharay et al., 2000), and risks for human health (Agne, 1996; Beck, 1997) as well as for the environment (Reynolds, 1991; Boyce et al., 1994; Babbar and Zak, 1995). Studies in Nicaragua concluded that, despite a thirty-fold increase in pesticide use and a ten-fold increase in fertilizer use in intensive production systems vs. traditional systems with shade, the traditional low-input technology was less risk prone (Table 1) (Clemens and Siman, 1993). However, although small growers with shade-grown coffee have avoided the major pest problems associated with open-sun

Table 1. Comparison of input levels, costs, and profitability in shaded traditional coffee and open-sun high-input coffee in Nicaragua.

	Yield	Pesticide use		Fertilizers		Total costs	Profit	Rate of return
	kg ha^{-1}	sprayings ha^{-1}	\$ ha^{-1}	kg ha^{-1}	\$ ha^{-1}	\$ ha^{-1}	\$ ha^{-1}	%
Shaded traditional technology	315–630	0–1	3	0–200	33	300	243	73
Open sun, high input technology	1,365–2,730	3–7	95	650–1,300	373	2,002	572	28

Source: Clemens and Siman (1993).

high-input coffee, many traditional systems have suffered from introduced pests, such as rust and berry borer, which farmers are not accustomed to managing.

In recent years, rust-tolerant varieties (the group of 'Catimores') have offered a non-pesticide option for managing this pest (Bertrand et al., 1999). However, employing these varieties continues the pest-by-pest approach used in chemical pest control; they simplify coffee rust management, but have proven to be more susceptible to other pests. For example, in more humid coffee growing regions of Costa Rica, American leaf spot levels have increased with the use of rust-tolerant varieties, such as Catimor 5175 (Wang and Avelino, 1999), while in Nicaragua mealybug infestation seems greater on these rust-tolerant varieties (M. Baylon, pers. comm., 2000).

Food web analysis: a hypothesis and an analytical tool

The recent history of coffee pest management suggests that agricultural fields should be treated as complex ecosystems with similar structure and function as natural ecosystems (Croft and Hull, 1983; Altieri, 1995; Gliessman, 1998). In order to achieve this, the current pest-by-pest approach of chemical pest-control strategies should be substituted by a broader focus on the pest complex as a whole, including insect pests, diseases, weeds, and nematodes. We hypothesize that, for each suitable combination of soil and climate for coffee, systems can be devised in such a way that the potential pest complex is at its minimum expression and the suppressive effects of associated beneficial microflora and fauna are maximized. In multistrata systems for coffee, the micro-environment determining the dynamics of pests and their controlling organisms depends largely on the species composition, planting density, spatial arrangement, and management of the trees that are associated with the coffee (Muschler, 1999). Pest dynamics can be used as indicators for adjustments of the tree component and its management, particulary through pruning and thinning, to address site-specific problems. For example, persistently high levels of leaf diseases associated with high light levels would signal a need for additional shade tree planting. In order to achieve the optimum shade environment to reduce critical leaf diseases, shade levels typically have to vary among seasons and years to compensate for climatic variability and to account for the changing requirements of the coffee plants throughout their phenological cycle. Other pest management interventions such as sanitary pruning of coffee plants or spraying are also subject to this site and temporal variability.

In order to analyze the interactions in time and space among trees, coffee plants, and the other flora and fauna, as influenced by the microclimate of the multistrata tree crop system, we employ the framework of a food web (Prokopy, 1994; Bugg and Waddington, 1994). Using examples from arabica coffee, we first analyze the role of climate, soil, and the modifying effects of shade on crop growth and phenology. Next, we identify autotrophs, herbivores, and secondary consumers in the coffee system, analyze their response to shade, and describe how they interact during an annual cycle. With this information we then illustrate how to identify the optimum range of shade for minimal expression of the coffee pest complex for different coffee zones in Central America and also propose annual shade regimes to create more pest-suppressive conditions for each season of the year.

Effects of climate and shade trees on different trophic levels

Effects on autotrophs

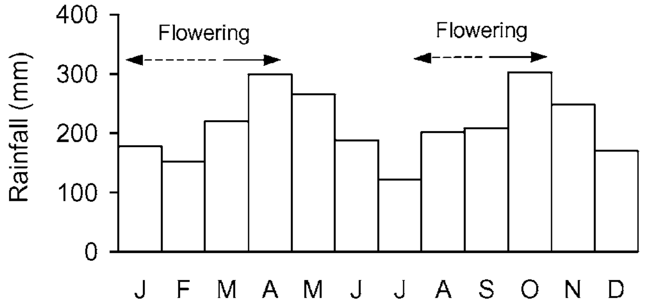
Climatic effects on coffee

The predominant autotrophs in multistrata perennial crop systems are often assumed to grow under ideal climatic conditions. However, in practice, most perennial crops suited for multistrata associations are grown under diverse and often adverse conditions. Arabica coffee is grown in tropical regions from 400 to 2,000 m a.s.l., with 1,000 to 3,000 mm annual rainfall distributed over six to 12 months. The average rainfall and temperature conditions at a specific site influence crop vigor and phenology, in particular the periods of new shoot and leaf growth, flowering, and leaf fall. Most coffee regions of Central America have a dry season of more than three months, after which the first rains trigger a marked peak of flowering. However, there are also many regions, such as the Atlantic region of Costa Rica, with virtually no dry months and, consequently, in several flowering peaks throughout the year. As shown later in the paper, the duration of rainy and dry seasons also influences pest cycles.

The climatic conditions at a particular site are typically characterized by long-term averages. However, unfortunately, averages often mask occasional large variability of rainfall and temperatures between years that can play a critical role for short-term management decisions. For example, for the hills around Managua, Nicaragua, the average rainfall pattern of Figure 1 occurs rarely; in the six-year period from 1992 to 1998, the annual rainfall varied three-fold, affecting strongly both coffee phenology and microclimatic conditions in the plantation. In the same period, May rains varied six-fold, and were often followed by either dry periods or excess rain in June, both of which can reduce flower set. Year-to-year variability also may shift the primary flowering flush and the moment of reaching the critical level of 10% of the leaves infected with leaf rust by up to two months (Monterroso, 1993; Figure 2). Another example is the incidence of occasional frosts, which damage coffee plantations at high altitudes and in southern Brazil (Coste, 1980). This year-to-year variability in weather can be mitigated by shade, but still has often drastic consequences for coffee growth, yield, and pest problems.

Shade tree effects on microclimate and coffee

Shade modifies local microclimate primarily by reducing available light by up to 60–80% (Goldberg and Kigel, 1986; Muschler, 1998). Light transmitted through a leaf canopy is also depleted in red wavelengths affecting seed dormancy, specific leaf area and architecture of understory plants (Attridge, 1990; Kozlowski et al., 1991). The presence of *Inga* shade trees (205 trees ha^{-1}) reduced daily temperature maxima by 4–5 °C and dampened daily fluctuations from 18 °C in open sun to 11 °C in shade (Barradas and


a) Monthly rainfall - Chinchina, Colombia

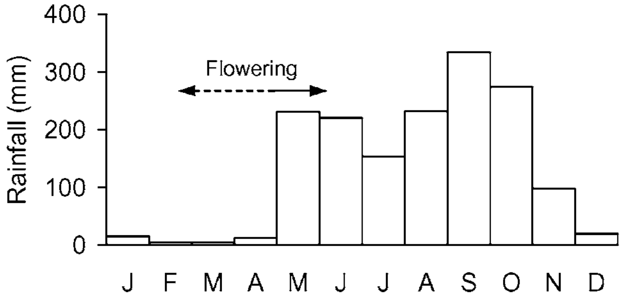

b) Monthly rainfall - Masatepe, Nicaragua

Figure 1. Average monthly rainfall and coffee flowering periods for (a) a year-round wet site and (b) a site with a prolonged dry season in Nicaragua (*Source:* Proyecto MIP-NORAD, Nicaragua).

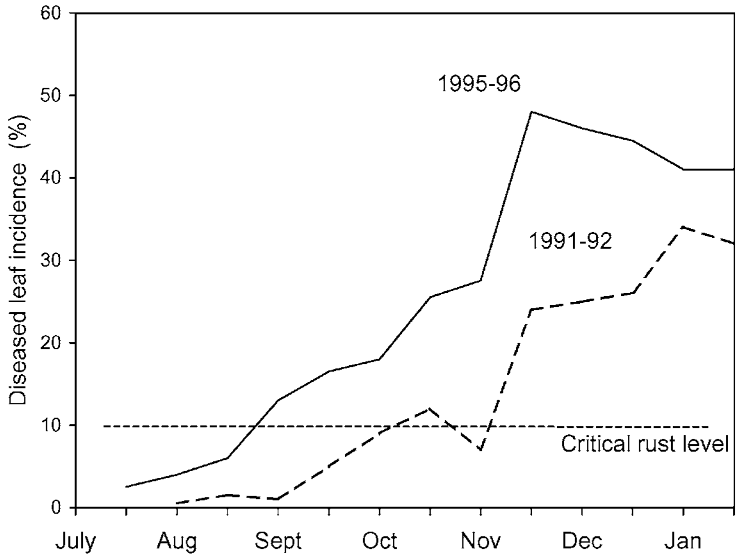


Figure 2. Wet season coffee rust dynamics in the Pacific uplands of Nicaragua. The critical 10% level was reached in early September in 1995 and in mid-October in 1991 (adapted from Monterroso, 2000).

Fanjul, 1986). Similarly, 40 to 70% shade from *Erythrina poeppigiana*, a common leguminous shade tree in Costa Rica, lowered leaf and soil temperatures in a low elevation coffee zone (700 m a.s.l.) to optimum levels for coffee (Muschler, 1998). Furthermore, shade reduced strongly the vapor pressure deficit and, hence, monthly Piché evaporation by 20–35% (Barradas and Fanjul, 1986; Muschler, 1998). The degree of microclimatic modification depends on the architecture and phenology of each tree species, but differences among tree species are not yet well documented. Central American farmers often characterize trees as hot (in Spanish *caliente*) or cool (in Spanish *fresco*) with respect to their effects on coffee (Table 2).

Shade has direct effects on coffee growth, yield, and quality characteristics that must be considered in designing the tree component. Particularly in low-elevation and warm environments, shade levels above 40 to 60% can help maintain air and leaf temperatures below or close to 25 °C (Muschler, 1998), a critical value for coffee (Kumar and Tieszen, 1980; Nunes et al., 1968). Higher leaf temperatures reduce photosynthesis. Very high values, especially when associated with

Table 2. Farmer categorization of tree species commonly used for shade in coffee in the Pacific Uplands of Nicaragua. Farmers mentioned 65 additional species less frequently.

'Cool tree' species*	% of farmers who mentioned species	'Hot tree' species *	% of farmers who mentioned species
Gliricidia sepium	85	*Cordia alliodora*	30
Enterolobium cyclocarpum	41	*Ficus hemeleyana*	26
Simarouba glauca	39	*Cedrela odorata*	25
Ficus hemeleyana	28	*Guazuma ulmifolia*	20
Inga spp. (I. vera, I. paterna)	37	*Lonchocarpus parviflorous*	15
Amphipterygium adstringens	18		
Pithecellobium saman	16		

* Identification from local names given by farmers.

Source: Mason Westphal, unpublished data from survey of 61 small farmers (1999).

abrupt changes from shade to sun, can disrupt normal physiological processes (Nunes et al., 1993), result in foliar nutrient deficiencies (Müller, 1959; Muschler, 1998), and reduce leaf retention. Monterrey (1990) found that in shaded coffee, leaf fall and new leaf emergence were delayed by several weeks (Figure 3). Slower leaf turnover under shade was also reported by Muschler (1998) and Samayoa (1999). In unshaded coffee fields, soil temperatures above 35 °C at two cm depth (Muschler, 1998) may reduce fine-root densities and foster imbalances in the soil biota, such as the higher nematode populations discussed below. In contrast, in coffee fields with at least 50% shade, soil temperatures never exceeded 21 °C.

Reports in the literature about shade effects on coffee yield are contradictory, probably due to differences in biophysical environments, plant materials, evaluation criteria, and length of studies (Cook, 1901; Willey, 1975; Fournier, 1988; Beer et al., 1998). The main factors governing coffee shade responses are probably elevation and soil fertility (Fernandez and Muschler, 1999). Under optimum conditions, in Central America often between 900 and 1,300 m a.s.l. on highly fertile flat soils, shade removal has been shown to increase production from 10 to 30%, at least in the short or medium term, without affecting coffee quality (Guiscafre-Arrillada, 1957; Ostendorf, 1962; Pérez, 1977). In these cases, light, rather than other factors, was limiting. In some cases, even higher increases were achieved, although coffee quality declined (Suárez de Castro et al., 1961; Abruña et al., 1966). While these data illustrate the production potential of coffee under ideal conditions, they are of limited value for sub-optimal conditions for coffee due to soil or climate limitations, often exacerbated by higher pest and disease stress. Under such suboptimal conditions, typical for many Latin American coffee zones, shade is essential for sustained production and quality. For example, in low-elevation (therefore high temperature) commercial farms on the Caribbean side of Costa Rica, coffee plants under intermediate homogeneous shade (30% to 50% photosynthetically active radiation PAR) of *E. poeppigiana* produced equally well as those grown without shade (Muschler, 1998). At the same time, they had healthier fruits giving higher quality coffee (Muschler, 2001), showed less or no foliar deficiencies, and retained more foliage at the end of the harvest period.

Shade tree effects on weeds

Besides coffee and trees, the other important autotroph component is weeds, which may affect coffee growth and yield. Weed biomass depends largely on the amount of light filtering through the tree and coffee canopy. For a Costarican coffee system, Muschler (1998) documented a decline from 3.6 Mg weeds ha^{-1} in unshaded coffee plots to less than 0.1 Mg ha^{-1} under 50% or greater shade. Similarly, Nestel and Altieri (1992) found over twice as many weeds in open sun than in multistrata coffee in Mexico. Also the weed species composition changed. Under shade

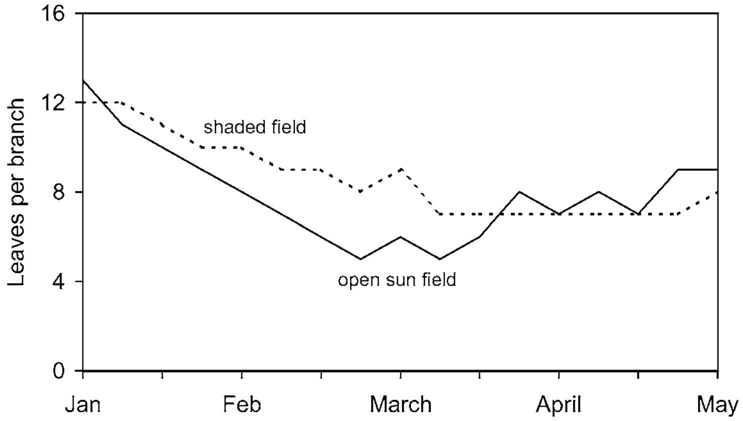


Figure 3. Effect of open sun and shade on coffee leaves per branch during the five-month dry season in the Pacific uplands of Nicaragua (Monterrey, 1990).

Commelinaceae dominated, species that compete little with the crop and are easy to control, whereas in open sun aggressive *Poacea* and *Compositae* were common. However, problematic vines like *Syngonium podophyllum* and shrubs may proliferate under shade.

Besides their shade effect, trees also suppress weed growth through the litter layer which forms from natural leaf fall and pruning residues. In studies with leaf prunings from *Inga paterna*, *Amphipterygium adstringens*, *Gliricidia sepium*, and *Simarouba glauca* applied to open sun and shaded coffee plots, weed numbers were reduced relative to unmulched controls for up to 60 days depending on mulch thickness and tree species (Staver, 1998). Tree leaf mulch alone was less effective in reducing total weed biomass, except when the most decomposition-resistant species were applied at double thickness. Mulch decomposed faster in shade than in open sun. However, even in open sun, *G. sepium* decomposed rapidly, losing 65% of its initial biomass in 63 days, even when applied at double and triple thickness. In contrast, *I. paterna*, *S. glauca*, and *A. adstringens* lost only 15% of their biomass in the same period. Under more humid, shaded conditions, all species had decomposed to small leaf fragments by 65 days, although *A. adstringens* leaf litter was more intact than leaf litter from *G. sepium*. Certain tree species common in coffee fields have been shown to have allelopathic effects on understory vegetation (Anaya et al., 1982), but their effects have not yet been used consciously to manage undesired plants.

Shade tree effects on herbivores and diseases

Herbivores feed on autotrophs of the multistrata crop system. The primary herbivores of the coffee plant are insects, fungi, and nematodes (Table 3). These herbivores may be specialist feeders depending on only one plant species like coffee or generalists which can feed on many species or have alternate hosts. Most coffee herbivores are specialists (Table 3) and, hence, their management does not require consideration of possible interactions with other plant hosts in surrounding areas, although there are exceptions such as nematodes, American leaf spot, and mealybugs. Selected weed and certain tree species are hosts to specific *Meloidogyne nematodes* (Baeza et al., 1978). American leaf spot infects many species under artificial inoculation (Sequeira, 1958), although in practice few species are natural hosts (Wellman, 1961). Mealybugs that feed on coffee also feed on *Annona* spp., *Psidium guayava*, *Theobroma bicolor*, *Ceiba* spp., and some trees used for coffee shade (Le Pelly, 1943; Cardenas, 1985). Varietial resistance for pest management has been developed primarily through the use of *C. canephora*. For example, to overcome nematode problems, *C. arabica* buds can be grafted on nematode-resistant rootstocks of *C. canephora* and partial or total resistance to coffee leaf rust has been obtained by crossing rust-susceptible *C. arabica* varieties with rust-tolerant Timor hybrids derived from interspecific crosses with *C. canephora* (Bertrand et al., 1999).

For the design of pest-suppressive multistrata systems, it is fundamental to know the response of each coffee herbivore to reduced light and increased humidity under shade. The general responses of leaf diseases, insect pests, and other herbivores to these factors (Table 3) are described in the following sections. However, few studies are available on herbivore responses to shade levels or shade from different tree species. This critical work remains to be done to permit site-specific design of pest-suppressive coffee systems.

Leaf diseases

Coffee leaf rust and brown eye spot, the two most commonly occurring coffee diseases in Central America, have contrasting responses to shade (Monterroso, 1999). In a comparative study of shaded (80%) and open-sun coffee fields in the uplands of southern Nicaragua, rust levels were higher in the shade (Figure 4), particularly in the lower parts of the coffee plants; this was attributed primarily to increased humidity. The key role of humidity was demonstrated by the fact that rust levels increased and decreased in the same periods of the year independent of shading. Brown eye spot, on the other hand, proliferated both on leaves and fruits only under little or no shade (Figure 4), being particularly marked on the sun-exposed parts of the plants; it is often accentuated by nitrogen and potassium nutritional stress (Wrigley, 1988). Higher levels of brown eye spot infection and reduced leaf and berry retention in open sun

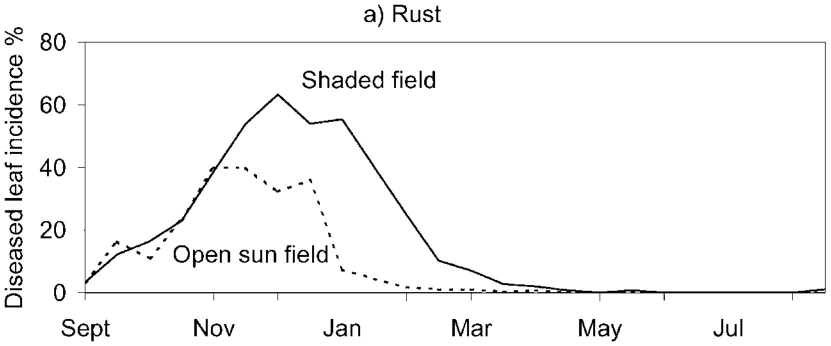
Table 3. Life form, hosts, and response to shade and humidity of generalist and specialist herbivores and of secondary consumers in agroforestry systems with *Coffea arabica*.

Generalist and specialist herbivores	Life form	Alternate hosts	Affects varieties differently	Response to shade*	Response to greater humidity*
Cercospora coffeicola	fungus	none	yes	– – –	0
Colletotrichum spp.	fungus	erratic	yes	erratic	erratic
Hemileia vastatrix	fungus	none	yes	0	++
Mycena citricolor	fungus	yes	yes	0	+++
Pellicularia koleroga	fungus	none	not verified	0	+++
Phoma costarricensis	fungus	none	not verified	0	+++
Meloidogyne incognita	nematode	yes	yes	0	++
Hypothenemus hampeii	insect	none	not verified	erratic	0
Leucoptera coffeella	insect	none	not verified	0	– – –
Planococcus citri	insect	yes	not verified	0	– – –

Secondary consumers	Life form	Coffee pest consumed	Other feed sources	Response to shade*	Response to greater humidity*
Beauveria bassiana	fungus	berry borer	other insects	++	++
Verticillium lecanii	fungus	leaf rust	insects	0	+++
Cephalonomia stephanoderis	insect	berry borer	none	0	+
Spore-consuming insect	insect	leaf rust	other rust spores	not known	not known
Nematotrophs	nematode	nematodes	diverse	0	++

* The responses, based on field observations, are given on a qualitative scale from a negative response (–) to a positive response (+) to the mentioned factor. No response is indicated by 0, and strong or very strong responses by two or three signs.

a) Rust



b) Brown eye spot

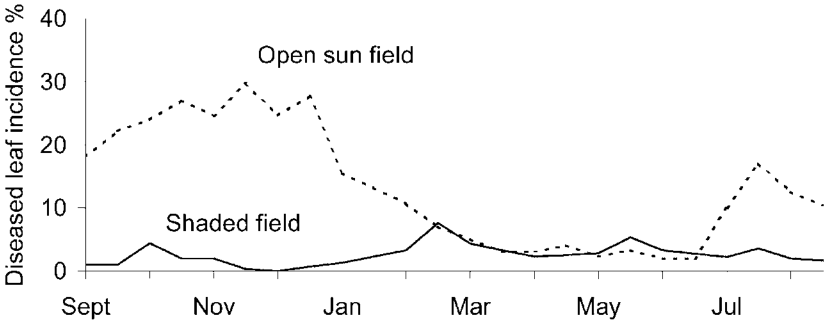


Figure 4. Effects of open sun and shade on coffee rust and brown eye spot dynamics in the Pacific uplands of Nicaragua (after Monterroso, 1999).

compared to shaded coffee was also reported by Muschler (1998) and Samayoa (1999) from Costa Rica. This contrasting behavior of two important coffee diseases presents a major challenge for designing the optimum shade component in coffee systems, since too much or too little shade will favor one or the other of the two diseases. However, in most coffee fields, only one disease dominates and can therefore be controlled by choosing appropriate levels of shade.

The diseases *M. citricolor*, *Phoma costarricensis*, and *Pellicularia koleroga* are positively and more uniformly correlated with humidity (Table 3). All three diseases are favored by the presence of a water film on the coffee leaves, a condition more frequent at higher altitudes, under heavy clouds or fog, and with more continuous rains. Heavy shade may accentuate high humidity by limiting light penetration and air circulation, factors that speed coffee leaf surface drying. In addition to reducing shade, other design elements, such as wider plant spacings, coffee pruning by entire rows, and stem and branch pruning to open coffee plants, may also contribute to more rapid drying of coffee leaves (Wang and Avelino, 1999). Finally, *Colletotrichum coffeanum* and *C. gloeosporioides*, two diseases causing necrotic spots on leaves and branch or stem dieback in extreme cases, may have a less marked response to the light or humidity effects of shade (D. Monterroso, pers. comm., 2000). However, they are known to particularly affect plants weakened by nutritional stress or overproduction, conditions which are more frequent under little or no shade and sudden abrupt changes of shade levels.

Insect pests

The three major coffee insect pests respond differently to shade. For the coffee borer, the results from field studies are contradictory. While numerous authors affirm that shade favors growth of coffee berry borer populations and, hence, borer damage to the fruits (Bergamin, 1945; Graner and Godoy, 1959; Alonzo, 1984; Quezada and Urbina, 1987; Decazy, 1988; Barrera, 1992), Monterrey (1991) failed to find any difference in coffee berry borer infestation between shaded (50–60%) and unshaded coffee fields in Nicaragua. From a three-year study in Honduras, Muñoz et al. (1987) concluded that coffee berry borer damage was highest in moderate shade, whereas the heavily shaded coffee suffered significantly less damage in comparison to coffee grown without shade. Coffee berry borer infestations tend to be higher in the lower half of the plant. While Alonzo (1984) attributed this to the more shaded conditions of the lower half of the plant, Muñoz et al. (1987) concluded that it was caused by the higher number of fruits available, since these authors did not find temperature or humidity differences among the different parts of the plant.

The coffee leaf miner is a pest of the dry season, generally believed to cause greater leaf fall in open sun coffee plantations (Sequiera and Hidalgo, 1979), presumably due to higher temperatures and lower humidity which accelerate larval development and population growth (Konnorova, 1980). However, independent of shading, the incidence of leaf miner is generally greater on the lower branches of coffee plants, possibly due to protection from direct exposure to sunlight and other adverse climatic factors (Pensado, 1982; Lescay, 1987; Gallardo, 1988). A study on the Pacific plains of Nicaragua during the dry season failed to detect differences between shaded (30–40%) and open sun coffee for leaf miner incidence, severity of damage, or total leaf area (Monterrey, 1990). However, towards the end of the dry season, leaf miner damage contributed significantly to leaf fall, particularly in plots without shade. This leaf fall is especially detrimental in unshaded coffee, since young leaves emerge in the late dry season instead of the early rainy season, as they do in shaded coffee (Figure 3).

Mealybug outbreaks occur in the dry season. Shade reduction caused wide-scale mealybug outbreaks in plantations of *C. canephora* in India (Venkataramaiah and Ramaiah, 1988). In Cuba, *C. arabica* plots with less than 30% shade had more mealybugs than plots with more shade (Martínez and Suris, 1999). Mealybug population growth and spread is favored by higher temperatures in open-sun conditions. High humidity slows population growth (Kumar, 1987).

Other herbivores

Shaded coffee fields also host many other herbivores that feed on weeds or tree species. Plantations with more diverse shade strata offering a greater variety of food sources (flowers, fruits, extrafloral nectaries, tender foliage) and habitat have been shown to permit greater herbivore diversity (Perfecto et al., 1996). While higher plant diversity, unless it includes alternate hosts for coffee pests, does not affect the coffee plants directly, it could contribute to increase the numbers and diversity of generalist predators which also feed on coffee pests. In addition, mixed shade may be less vulnerable to the herbivore outbreaks that occasionally can defoliate monospecific shade strata, such as those reported by farmers involving the *Inga* specie commonly found as the sole shade species in coffee fields. Other agroforestry species, when planted as single species stands, such as *Leucaena leucocephala* have suffered devastating pest outbreaks in the past (Huxley, 1999).

Shade tree effects on consumers

Secondary consumers complete their life cycles by feeding on the energy and nutrients of herbivores and diseases such as berry borers and coffee leaf rust. Without these naturally occurring insects and fungi, pest levels would escalate. Understanding whether they are specialists or generalists and what conditions favor their presence and activity is essential for designing pest-suppressive multistrata systems (Table 3). Many beneficial species are favored, at least during part of their life cycle, by a buffered shade environment. Direct solar radiation reduces germination of the conidias of the entomopathogenic fungus *Beauveria bassiana*, the most common natural control agent of the coffee berry borer. In contrast, shade favors *B. bassiana* by extending the viability of the conidias and by providing sufficiently high humidity in the coffee plantations for an epizootic of this fungus (Velez, 1993). However, Pascalet (1939) stated that both conidia dispersal and sporulation of *B. bassiana* on the integuments of the affected insects are generally favored by lower humidity and more light. Thus, this natural control agent may be most effective in a managed (variable) shade environment rather than in one with dense or no shade, since different conditions favor hyphal growth as sporulation and conidia dispersal. *Verticillium* fungi, hyperparasites of coffee leaf rust spores, are favored by higher humidity. They are relatively infrequent during the early and midseason rains, but are more common late in the rainy season, particularly in shaded and humid conditions. This pattern suggests that *Verticillium* could be effective in reducing the residual spores of coffee leaf rust that are carried over to the following season (Monterroso et al., 1995).

A managed shade environment also favors the action of other control agents of coffee berry borers like the parasitic wasps *Prorops nasuta* and *Cephalonomia stephanoderis*. In densely shaded plantations, *P. nasuta* acts only when the infestation of coffee berry borer reaches a very high level, whereas in moderate shade it is more capable of regulating the population growth of the coffee berry borer (Bergamin, 1949). Hargreaves (1935) proposed that parasitoids prefer less shade, thus contributing to lower borer infestations in coffee plots without shade in Africa where the parasitoids are native. However, the documentation of shade effects on parasitoids is sparse. In Nicaragua, a still unidentified spore-feeding insect (Cecedomyiidae) is frequently found on rust lesions both on weeds and coffee (D. Monterroso, comm. pers.), but neither the insect dynamics nor its interactions with the weeds have been studied so far. One apparent host plant, *Alternanthera pubiflora*, is a tall and aggressive weed which would need special management in order not to compete with coffee plants.

The presence of diverse shade strata favors generalist predators like spiders and ants (Perfecto et al., 1996). In coffee plots with diverse tree species, Ibarra (1990) found arthropods belonging to 21 orders, 258 families and 609 species, a level of diversity similar to a natural forest. A recent study from Nicaragua also found more insect species in shaded than unshaded coffee plots (Monterrey et al., 2001). The diversity and number of individuals and insect families increased with the diversity of the shade trees present in the coffee plots (Table 4). Little is known about the effects of specific tree species on secondary consumers.

Shade tree effects on soil-borne pests and detritus feeders

The final dimension of the food web is the detritus feeders. In shaded coffee, the detritivores feed on 5–20 Mg ha^{-1} yr^{-1} of leaf and branch organic

Table 4. Insect faunal diversity in multistrata coffee systems in the Pacific region of Nicaragua.

	Dense shade with multiple tree species	Moderate shade with multiple tree species	Moderate shade with one tree species	Without shade
Total insects captured in traps	489	158	132	24
Insect families captured in traps	12	11	9	2

Source: Monterrey et al. (2001).

matter supplying the soil with energy and nutrients (Beer, 1988). The level of soil organic matter appears to be a key factor for determining the activity of plant-parasitic organisms like *Fusarium* spp., *Rosellinia* spp., or nematodes which, acting together, have been made responsible for a slow wilt syndrome known as 'mal de viñas' or 'muerte misteriosa' and which, as a result, cause concern in some sun-grown coffee plantations in Central America (CATIE-PROMECAFE, 1996; Sumner and Hylton, 1994). Studies of soil fauna in sun vs. shade-grown coffee are rare and often incomplete. In Nicaragua, a shaded coffee plot had nine plant-parasitic species and two free-living nematode predator species compared with only seven plant-parasitic species and no free-living predator species in open sun (Cruz et al., 1998). While nematode diversity was greater in shade, nematode counts of the plant-parasitic *Meloidogyne* spp. were 200 fold greater in unshaded than in shaded coffee plots. A similar tendency in Costa Rica was also reported by Samayoa (1999), who found lower *Meloidogyne* populations in organic coffee plots under 30–60% shade relative to conventional plots with less than 30% shade.

Appropriate shade levels for suppressing the pest complex

In order to design a pest-suppressive tree component for coffee, the information of the previous sections on the shade response of individual pests must be integrated into a single framework. Eventually such a framework might become a decision-support system or a mathematical model. As a first approximation here, we used an additive approach, which qualitatively sums the negative relative impact of each factor on potential coffee productivity (Figure 5). The curves in Figure 5 represent the hypothesized (because inadequately researched) trends for the different factors based on field observations, research, and relevant literature. Attempting to graph the effect of each pest to varying shade levels revealed large gaps in our current understanding of the systems. Most papers which compare open sun and shaded conditions do not quantify shade levels or describe the seasonal shade dynamics. We could not find quantitative studies on the effect of individual tree species on pest dynamics. Despite the dearth of quantitative data available, we attempted to rank the pests from most to least serious for different shade levels. For a typical coffee zone at low altitude (600 to 900 m a.s.l.), with a dry season of more than three months, 1,200–2,000 mm annual rainfall, and modest agrochemical inputs, i.e., many coffee zones of Central America with Pacific influence, shade levels should range from 35% to 65% (Figure 5). Within this shade range, the negative effects of the pest complex are likely at a minimum, while coffee yields would not be reduced strongly due to excessive shade. Consequently, yield of healthy coffee berries would be highest for this range of shade. Similar figures could be developed for other climatic regions. In higher, wetter zones, the importance of brown eye spot declines. *P. costarricensis*, *M. citricolor*, and *P. koleroga*, which are virtually absent in low, dry coffee zones, increase with elevation. Therefore, the optimum shade range for higher, wetter coffee zones would be lower, even though costs for weed control would likely increase.

The identification of the desired range of shading provides the central guide for designing pest-suppressive shade strata. To achieve the desired shade levels, single- or multiple-species stands can be used, consisting of fruit, timber, or service trees (Beer et al., 1998; Muschler, 1999). Tree density and spatial arrangement can be adjusted to suit size, canopy density, phenology,

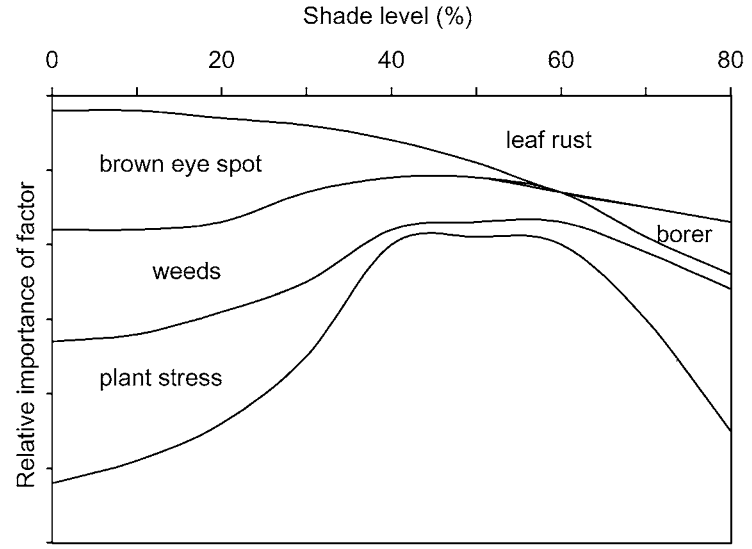


Figure 5. Conceptual graph depicting the relative importance of yield-reducing factors in a low, dry coffee zone in Nicaragua. Effects are shown to be additive with the effect of each successive pest represented by the area between the lines. The lowest line indicates the accumulated potential for yield reduction at different shade levels. Since the y-axis is negative, the range of least yield reduction is 35 to 65%.

and management of the trees. An analysis of seasonal shade requirements provides an additional guide for designing appropriate tree components and adequate pruning regimes.

Managing the tree component to suppress pests

The establishment of pest-suppressive systems reduces the need for direct pest control measures and the associated costs and impacts. The first step to design and manage pest-suppressive systems is to determine the appropriate range of shade levels for different coffee growing regions. Up to now, we have summarized the general responses of primary producers, herbivores, and consumers to the light and humidity effects of shade. In this section, we elaborate our initial characterization of the food web according to the major seasons and crop cycle stages during the year. For each season, we locate the organisms by life cycle stage within the coffee system (Table 5). A seasonal analysis of the factors favoring the presence or activity of the organism, whether it be an autotroph, a herbivore, or a consumer, allows us to exemplify three types of practices for the design and management of the tree component in order to facilitate pest suppression by season (Table 6). Shade can be designed and managed (1) to strengthen crop tolerance or capacity to recover, (2) to create unfavorable conditions for pests, or (3) to create conditions that favor natural biological control mechanisms. Only practices relating to the tree component will be discussed here. A more complete description of coffee pest management in Central America, including tactics for direct pest control, can be found in Guharay and Monterrey (1997), Staver (1998), Bertrand and Rapidel (1999), Monterroso (1999), and Guharay et al. (2000). Finally we integrate the management of the tree component season by season for the suppression of weeds, diseases, and insects for a low, dry coffee zone (Figure 6).

Weed management

Weed growth is concentrated primarily in the rainy season with seed production occurring at the end of the rainy or the beginning of the dry season (Table 5). Where vigorous coffee bushes provide a closed canopy for the ground, weed growth is reduced. However, the alleys between the rows

Table 5. The life cycle stage of coffee pests and beneficial organisms by season of the year in coffee regions with a dry season longer than three months.

Organism	Dry season	Early rains	Mid season rains	Late rains/early dry season
Annual weeds	seed bank	flush of germination	vegetative growth/seed production	seed production
Perennial weeds	restricted growth	——————————— vigorous growth ———————————		seed production
Berry borer	survival and reproduction in unharvested berries on ground and plant	adults reproduce in developing berries originating from first flower flush	adults reproduce in berries originating from later flowering flushes	adults continue reproduction in remaining berries
Leaf miner	accelerated reproduction on newly emerging leaves	high mortality with first rains	—————— limited reproduction on lower leaves ——————	
Mealybugs	accelerated reproduction in large colonies	increased mortality with first rains	— survival as dispersed individuals on coffee and alternate hosts —	
Brown eye spot	lesions with limited activity on isolated leaves	infectious spores produced on isolated or fallen leaves	acceleration of infection rate and of spore production in upper leaves	leaf fall and continued spore production
Rust	inactive lesions on isolated leaves; leaf fall	lesions reactivated; infection of new leaves in lower strata	acclerated infection and spore production on leaves of lower and middle strata	disease reaches upper leaves; beginning of leaf fall
American leaf spot	inactive lesions on isolated leaves and alternate hosts	reactivation of lesions and infection of new leaves	accelerated infection and spore production	leaf fall and continued spore production
Anthracnose	inoculant in dead branches	reactivation of growth from over wintering structures	accelerated infection of additional leaves and branches and increased spore production	leaf fall and branch dieback and continued spore production
Beauveria bassiana	dry season survival as spores	spore dispersal and new mycelial growth	accelerated mycelial growth in shaded conditions	sporulation in response to light and dry conditions
Verticillium lecanii	dry season survival as spores and as saprophitic growth	reactivation of infections in isolated microsites of high humidity	accelerated infection	greatest abundance in response to increased rust
Cephalanomia stephanoderis	high reproduction due to drying conditions and abundant berry borer	high mortality and low reproduction due to rains and limited host populations	continued high mortality due to rains, although increased host populations	increased reproduction due to increased host populations

Source: Adapted from Guharay et al. (2000).

Table 6. Specific shade management practices by season to strengthen coffee plant vigor and tolerance, to reduce conditions for pest growth and to improve conditions for biological control.

Organism	Objective	Dry season	Early rains	Mid season rains	Late rains/early dry season
Coffee	*Strengthen crop*	shade for extended leaf retention	application of nutrient-rich tree leaf prunings	———— partial shade reduces plant stress ————	
Weeds	*Reduce conditions for pest growth*	shade and limited water availability reduce weed growth	——— leaf litter, pruning mulch and heavy ——— shade reduces weed growth		leaf litter, pruning mulch and heavy shade reduces seed production
	Improve conditions for biological control	leaf litter/soil moisture promotes seed destruction by soil fauna	leaf litter and pruning mulch promote seed decay and reduce germination	— leaf litter and pruning mulch promote seed decay —	
Brown eye spot	*Reduce conditions for pest growth*	——————————————— moderate shade ———————————————			
	Improve conditions for biological control	—————————————— research needed on leaf surface flora ——————————————			
Leaf Rust	*Reduce conditions for pest growth*	decreased shade accelerates diseased leaf fall	—————— reduced shade for air movement and faster leaf drying; —————— wider spacing of coffee plants		
	Improve conditions for biological control	——————— increased shade promotes reproduction of antagonistic fungus *Verticillium* ———————			
Berry borer	*Reduce conditions for pest growth*		—————— avoid excessive shade ——————		
	Improve conditions for biological control	shade diversity for increased general predators	——— partial shade to promote *Beauveria* ——— mycelial growth		avoid excessive shade to promote *Beauveria* sporulation
Dry season insect pests	*Reduce conditions for pest growth*	shade and windbreaks; leaf litter for soil moisture maintenance	————— reduction of alternate hosts —————		shade and windbreaks to avoid rapid drying out of the plantation; leaf litter for soil moisture maintenance
	Improve conditions for biological control	moderate shade to promote natural control predators and fungi	————— shade and border species diversity for adult predator feeding —————		

Source: Adapted from Guharay et al. (2000).

receive more light and, consequently, weeds grow unchecked. Multistrata shade further reduces light levels and also provides natural leaf litter and pruning residues to diminish weed growth (Table 6). Leaf prunings and weed slashing can be directed selectively to reduce the growth and seeding of tall, aggressive weeds. Ground cover plants with low growth and shallow roots such as *Oplismenus burmannii*, *Drymaria cordata*, and *Panicum trichoides*, should be left uncontrolled for soil conservation (Staver, 1998). This management approach produces a mosaic of soil protection composed of leaf litter and ground cover weeds under a patchy shade environment of coffee and trees.

Leaf disease management

The microclimate created by managed multistrata shade modifies the annual cycle of the disease complex (Monterroso, 1993). New disease-free leaves emerge into residual inoculant from the previous year and become infected depending on the coffee variety, the physiological state of the leaf, and the light and moisture conditions. The design and management of multistrata shade should achieve moderate light levels without elevating humidity on the coffee leaf surface during critical high moisture periods (Table 6). Desirable shade percentages are lower under cloudier, cooler, and more humid conditions and higher under drier, hotter, sunnier conditions. Regular systematic disease monitoring provides criteria for adjusting shade patterns and intensities, and the application regimes of plant extracts to promote beneficial leaf flora or of fertilizers and fungicides if necessary. Other practices such as sanitary pruning and removal of diseased materials from the plantations are also important to reduce disease inoculant.

Berry borer management

Microclimate, particularly humidity, determines largely the development of hyperparasites such as entomopathogenic fungi. Although coffee berry borers appear to perform equally well in open sun and managed shade, naturally occurring *B. bassiana* multiplies and spreads more quickly with greater humidity (Table 5), and fungus applications should coincide with periods of high moisture (Guharay and Monterrey, 1997). If dispersal of the fungal conidia and sporulation is favored by lower humidity and more light (Pascalet, 1939), the highest effectivity of the fungus would be expected under managed shade with some seasonal variation of moisture and light rather than under dense or no shade. Such managed intermediate shade would also be likely to favor the parasitoids of the borer which are disfavored by heavy shade.

Management of dry season insect pests

The dry season pests of coffee can be managed through maintaining a multistrata system that provides shade and windbreak to keep the environment relatively cool and (less dry). Leaf litter and living ground covers conserve superficial soil moisture to reduce stress on coffee plants during the early dry months and delay the natural leaf fall and new leaf emergence. In shaded coffee, new leaf emergence occurs after the first rains. These rains are an effective control of the leaf miner. Thus in shaded coffee, newly formed leaves normally escape significant leaf miner damage. At the same time, the absence of spraying for leaf miner in the dry season permits a greater population of natural enemies, which also keep mealybugs in check. Higher diversity in the shade, windbreak, and ground cover species should also increase the availability of flower nectar to foment the survival of adult parasitoids of leaf miners and mealybugs.

Annual shade management for pest suppression

Two alternative approaches can be identified to achieve the intermediate shade conditions that benefit both coffee (vigor, production, and quality) and its associated food web. First, to minimize pruning costs, tree species that are self-pruning and that have relatively small and open crowns can be used that maintain shade at the lower limit of the optimal shade range (Figure 6). Species such as *Cordia alliodora*, *Grevillea robusta* or *Gliricidia sepium* have minimal pruning needs. Their shade fluctuates naturally throughout the year depending on leaf phenology and branch growth of each species. Due to these fluctuations, certain periods of the year may present less-than-optimum conditions for the coffee requirements or pest suppression, which may require some additional short-term pest management practices. The mix of several tree species in the shade overstory would reduce the fluctuation between excess or insufficient shade.

The second approach employs an annual pruning regime of the trees to suppress the different pests on the one hand, and to favor their biological control agents and the coffee plant itself on the other. To illustrate this approach, we will again use the low altitude coffee zone with a marked dry season as an example (Figure 6). During the extended dry season, higher shade levels are desirable for coffee leaf retention, control of dry season pests, and the survival of beneficial fungi. Shade should be above 50% during most of the dry season. However, less shade may promote the activity of *C. stephanoderis* and may also accelerate the abscission of diseased leaves. Since most shade trees are fully or partially deciduous during the dry season, the shade at the beginning of the dry season should exceed 50% and some non-deciduous species should be incorporated in the shade overstory. As the dry season advances, shade levels decline gradually due to leaf fall. Mixed shade species stands with non-overlapping periods of leaf turnover can avoid sudden reductions in shade levels due to leaf fall.

Shortly before or at the beginning of the rainy season, trees should be pruned moderately to favor drying within the plantations during the rainy season. However, some shade should be retained to minimize the spread of brown eye spot. Pruning opens up the plantation floor to light which stimulates weed growth, but also provides leaf mulch for weed control. Tree species with leaf material resistant to decomposition, for example *Inga* spp., help to extend mulch weed control for a longer period. In low altitude dry coffee areas, shade for coffee should be reduced from above 60% to 40–50%. As the rainy season progresses, humidity builds up accelerating the spread of coffee rust. Moderate shade would still be required to suppress weed growth and to reduce the spread of brown eye spot and its negative impact on fruit quality. To promote more rapid drying of the coffee leaf surface, another pruning around August should reduce shade levels to 35–40%. From this minimum of 35% shade in the middle of the rainy season, the shade should increase to about 50% at the end of the rainy season and exceed 60% early in the dry season. Shade should continue to increase into the early dry season before tree growth slows and leaffall begins.

Conclusions and recommendations

A pest-suppressive shade tree stratum in coffee plantations should have at least two tree species of contrasting phenology to maintain shade levels within the desirable range of 35 to 65% for most coffee zones and to avoid abrupt changes of

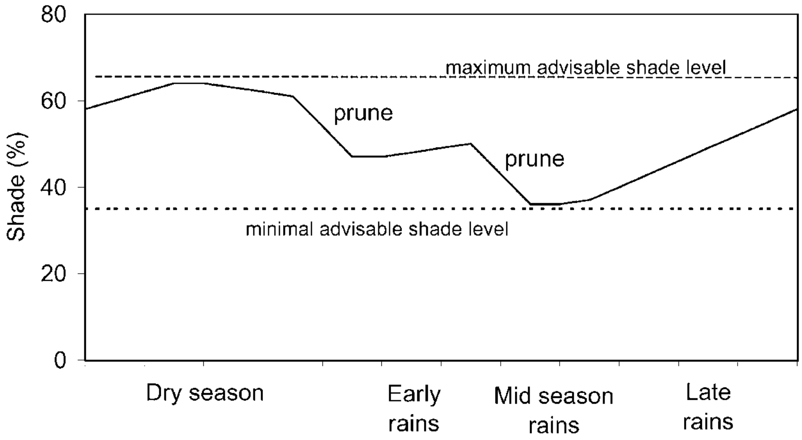


Figure 6. Proposed shade levels and management by season for maximum pest suppression for a low, dry coffee zone in Nicaragua.

shading resulting from leaffall. Their leaf and pruning litter should range from rapidly decomposing to decomposition-resistant materials for both fertilizer and weed suppression functions. Pruning regimes may be species-specific. The pruning of certain tree species prior to the first rains could be designed to provide decomposition-resistant pruning litter. Other species pruned during the middle of the rainy season could provide rapidly decomposing litter to make nutrients available to coffee.

Many issues merit further research in formal long-term systems studies, in on-farm trials, and in participatory research with farm families. First, the effects of individual tree species on coffee growth and production, microclimate, and the different components of the coffee food web need to be explored in more detail. Second, the canopy characteristics and shade patterns which promote coffee leaf drying, while reducing light levels, need to be defined. Third, the regrowth potential of trees after pruning at different times of the year needs to be assessed, since it is a central criterion for species selection. Fourth, frequent pruning of trees planted at higher densities should be explored to determine if litter production for weed suppression and nutrient supply to coffee can be increased without increasing competition. Lastly, research is needed on simple observation methods and decision criteria that can be used by farmers to guide their management of tree-coffee-pest interactions. Both the analysis of existing species associations in farmers' fields and formal large-plot long-term research will eventually provide recommendations for the selection and management of tree species and densities for coffee fields.

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