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Shade management in coffee and cacao plantations

J. BEER*, R. MUSCHLER, D. KASS and E. SOMARRIBA
Apdo. 44, Area of Watersheds and Agroforestry Systems, CATIE, Turrialba, Costa Rica
(Address for correspondence: E-mail: jbeer@catie.ac.cr)*

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Abstract. Shade trees reduce the stress of coffee (*Coffea* spp.) and cacao (*Theobroma cacao*) by ameliorating adverse climatic conditions and nutritional imbalances, but they may also compete for growth resources. For example, shade trees buffer high and low temperature extremes by as much as 5 °C and can produce up to 14 Mg ha^{-1} yr^{-1} of litterfall and pruning residues, containing up to 340 kg N ha^{-1} yr^{-1}. However, N_2 fixation by leguminous shade trees grown at a density of 100 to 300 trees ha^{-1} may not exceed 60 kg N ha^{-1} yr^{-1}. Shade tree selection and management are potentially important tools for integrated pest management because increased shade may increase the incidence of some commercially important pests and diseases (such as *Phythphora palmivora* and *Mycena citricolor*) and decrease the incidence of others (such as *Colletotrichum gloeosporioides* and *Cercospora coffeicola*). In Central America, merchantable timber production from commercially important shade tree species, such as *Cordia alliodora*, is in the range of 4–6 m^3 ha^{-1} yr^{-1}.

The relative importance and overall effect of the different interactions between shade trees and coffee/cacao are dependent upon site conditions (soil/climate), component selection (species/varieties/provenances), belowground and aboveground characteristics of the trees and crops, and management practices. On optimal sites, coffee can be grown without shade using high agrochemical inputs. However, economic evaluations, which include off-site impacts such as ground water contamination, are needed to judge the desirability of this approach. Moreover, standard silvicultural practices for closed plantations need to be adapted for open-grown trees within coffee/cacao plantations.

Introduction

In 1995, coffee (*Coffea* spp.) and cacao (*Theobroma cacao*) plantations worldwide totaled 16,700,000 ha (FAO, 1996). Plantations of these perennial crops are one of the most important forms of land use and are of enormous economic importance for developing countries in the humid tropics (Graaff, 1986; Wood and Lass, 1985). In addition to these crops, many other well-known perennials, such as black pepper (*Piper nigrum*) and vanilla (*Vanilla fragrans*), and lesser-known crops, such as Yerba mate (*Ilex paraguariensis*) (Evans and Rombold, 1984) and cupuazú (*Theobroma grandiflorum*) – a close relative to cacao (Duarte, 1992), are usually grown under shade trees (Purseglove, 1968; 1972); i.e., in agroforestry systems based on two or more perennial species (Nair, 1993). Nevertheless, unshaded intensively managed plantations have been promoted in some countries.

One reason for maintaining shade trees in perennial-crop plantations is the income provided by their fruit and/or timber; these products may supplement farmers' income when coffee/cacao prices are low. At a national level, increasing awareness of the environmental costs associated with high-input monocultures – for example, ground water pollution and soil erosion on sloping land in the case of coffee (Boyce et al., 1994; PROMECAFE, 1995) – has also led to renewed interest in the use of shade trees in areas where they had previously been eliminated. At the international level, attention has recently focused on the contribution of shaded coffee or cacao fields for maintaining biodiversity (Perfecto et al., 1996; Young, 1994) and for stop-over points for migrating birds (Wille, 1994). Low and variable prices for coffee and cacao, rising prices for inputs, and environmental problems have raised questions about the 'sustainability' of high-input, unshaded plantations and rekindled interest in the use of shade trees.

In this context, it is important to take stock of the accumulated information on shade trees. The purpose of this paper is to summarize the voluminous literature on ecological aspects of shaded coffee and cacao plantations, and on the productivity and management of the shade trees. The scope of the paper does not permit detailed discussion of socioeconomic aspects; however, a few salient features are mentioned. Finally, we discuss priority research topics relating to the ecology and management of shade tree systems. The emphasis of the review is on Central America, which is CATIE's mandate area, and where most of the reported work on the topic has been conducted.

The effects of maintaining shade trees over perennial crops were described as early as the late nineteenth century. For example, Lock (1888) provided a comprehensive description of the positive and negative effects of shade trees, based on studies of coffee management in Ceylon (now Sri Lanka) (Table 1). Sáenz (1895), Cook (1901), and authors from Colombia (FNC, 1932), Venezuela (INC, 1942) and Honduras (Ortega, 1951), also published early accounts of the potential role of shade trees over coffee. The relative importance of the different effects of shade trees, and hence the need for shade, is strongly affected by site conditions – a fact that has generated considerable

Table 1. Key aspects of shade and shade trees for coffee in Ceylon (now Sri Lanka).

- *Climatic range:* Shade is not universally beneficial. The need for shade is a function of climate (it is especially important in hot and dry climates).
- *Benefits of shade:* Diminished crop exhaustion, and increased longevity of coffee plants; reduced costs; maintenance/improvement of soil fertility; increased litter (and hence nutrient availability); value of timber.
- *Drawback:* Coffee yield reduction, but compensated by increased longevity.
- *Beneficial shade tree attributes:* Small foliage, provision of timber, fruit or other useful products, sub-soil feeder so that nutrients are recycled by fallen leaves.

Source: Lock (1888).

controversy concerning the use of shade (Willey, 1975; Beer, 1987). The increasing use of inorganic fertilizers and pesticides during the past fifty years, sometimes associated with partial or total elimination of the shade trees, has stimulated discussion on the advantages and disadvantages of shade trees, and their selection criteria (Willey, 1975; Beer, 1987; Wrigley, 1988; ANACAFE, 1991; Smith et al., 1992).

The major physiological benefits that coffee and cacao receive from shade trees can be placed into two main categories, both associated with reduced plant stress:

1) Amelioration of climatic and site conditions through (i) reduction of air and soil temperature extremes (heat at lower elevations and cold at higher elevations), (ii) reduction of wind speeds, (iii) buffering of humidity and soil moisture availability, and (iv) improvement or maintenance of soil fertility including erosion reduction; and
2) Reduction in the quantity and quality of transmitted light and hence avoidance of over-bearing (e.g., in coffee) and/or excessive vegetative growth (e.g., flushing in cacao). Shade reduces nutritional imbalances and dieback.

The main physiological drawback is competition, especially when excessive shade is used. If high agrochemical applications are feasible, for example when crop prices are high and environmental issues are not considered, maximum attainable yields per hectare are often higher without shade (Willey, 1975). In seasonally dry zones, root competition for water may limit the use of shade trees for coffee (Franco, 1951). Pest and disease problems may increase (Fonseca, 1939; Dakwa, 1980; Smith, 1981; Wrigley, 1988; ICAFE, 1989b) or decrease (Tapley, 1961; Ahenkorah et al., 1974; Nataraj and Subamanian, 1975; Smith, 1981; Eskes, 1982; Campbell, 1984) with increased shade. Yield potential, competition for water, and pest/disease incidence depend on site conditions, and are fundamental issues in the controversy over the use of shade trees in coffee and cacao plantations.

The plant-plant interactions associated with the above effects mostly occur indirectly via effects on the environment, i.e., the so-called ‘response (of the plant) and effect (on the environment)’ axiom (Goldberg and Werner, 1983). In this way, a shade tree species may increase (+), decrease (–), or have no effect (0) on the vigor and productivity of an associated crop species (Anderson and Sinclair, 1993). Most studies have emphasized the short-term effects of the shade species on the associated crop, for example, effects on crop yield, disease incidence and nutrient availability (Beer, 1987). Few studies, such as that of Ahenkorah et al. (1974), have evaluated the long-term effects of shade on crop vigor and productivity.

The characteristics of the shade stratum – as determined by the botanical composition, number of vertical layers (sub-strata), degree of canopy closure, tree crown characteristics, and shade tree management (pruning, thinning and/or replanting) – vary greatly between major ecological zones and between farms within each zone in response to both biophysical and socioeconomic factors (Somarriba et al., 1996). Highly diverse shade structures are typical of small farms in marginal or suboptimal sites (Jiménez, 1979; Escalante, 1985; Espinoza, 1985; Alcorn, 1989). Simple shade structures, and in the case of coffee, even high-input unshaded plantations, are often established by wealthy farmers on optimal sites or are maintained with external inputs on suboptimal sites, e.g., in Brazil, Colombia and Costa Rica.

Little socioeconomic research on shaded coffee or cacao systems has been published, and labor input, often a limiting factor in agriculture in the humid tropics, has received inadequate attention. An annotated bibliography of pre-1990 publications included only 17 references (mostly in ‘grey literature’) that presented financial and economic analysis of coffee- or cacao-shade systems (Swinkels and Scherr, 1991). However, this bibliography did not include all of the rich literature on intercropping cacao with coconuts, oil palm and rubber, systems now labelled as agroforestry (e.g., Lee and Kasbi, 1980; Pushparajah and Soon, 1986).

Agronomic consequences of using shade trees in coffee and cacao plantations

Soil organic matter and soil fauna

Soil organic matter (SOM) content may increase with time under agroforestry systems of coffee and cacao. For example, over a 10-year period following conversion of sugar cane fields to cacao plantations, SOM increased by 21 percent under pruned leguminous *Erythrina poeppigiana* and by nine percent under unpruned nonleguminous *Cordia alliodora* (Beer et al., 1990). Nair and Rao (1977) found that the association of cacao with coconuts increased the number of bacteria and fungi in the coconut rhizosphere. They attributed this positive effect to increased litter inputs. Maintenance of high SOM levels by shade trees might help to stabilize coffee nematode (*Meloidogyne* and *Pratylenchus* spp.) populations below critical levels (Araya, 1994). At the same time, the reduction of environmental stress provided by shade increases the tolerance of coffee plants to infestations of these nematodes (OFICAFE, 1978). However, an injudicious choice of the shade species could have the opposite effect. *Inga* spp., for example, have been identified as alternative hosts for coffee nematodes (Zamora and Soto, 1976) but it is not clear whether this would actually increase or decrease the nematode pressure on the coffee.

Biological nitrogen fixation

Management practices will affect N_2 fixation by leguminous shade trees in coffee and cacao plantations. Plantations may be heavily fertilized with N and other elements, or not fertilized at all (Wood and Lass, 1985; Wrigley, 1988).

Populations of leguminous shade trees may range from fewer than 100 trees ha^{-1} to more than 300 trees ha^{-1} (Ling, 1984; Barker, 1991). Shade trees in many plantations are allowed to grow freely while in more intensively managed areas several pollardings per year may be carried out. Pruning residues may be left around the trees, chopped and spread on the ground, or exported for fodder and firewood. All of these practices will affect levels of N_2 fixation and N availability in plantations. The choice of species, and even the choice of clones, will also affect N_2 fixation rates (Nygren and Ramírez, 1995).

Lindblad and Russo (1986) found levels of acetylene reduction in a heavily fertilized coffee plantation shaded with *E. poeppigiana* that were similar to those reported by Roskowski and van Kessel (1985) and Escalante et al. (1984) in unfertilized coffee and cacao plantations shaded with *Inga jinicuil*, *Gliricidia sepium* or *E. poeppigiana*. These latter authors reported N_2 fixation of 35–60 kg ha^{-1} yr^{-1}, but this may be an underestimate since the acetylene reduction method measures only short-term nitrogenase activity (Peoples and Herridge, 1990). However, Fassbender (1987), comparing the nutrient balances of leguminous and nonleguminous coffee-shade tree associations, also estimated that 60 kg N ha^{-1} yr^{-1} were fixed by *E. poeppigiana*. Nygren and Ramírez (1995) found that *E. poeppigiana* nodules disappeared almost completely for ten weeks after pruning, which suggests that there may be 20 weeks in the year during which these biannually pruned trees do not fix N_2 and compete with the associated crop for soil N. Herrera et al. (1987) reported that the nodules of unpruned *E. poeppigiana* shade trees in cacao plantations in Venezuela disappeared during the dry season.

The literature cited above reports relatively low contributions of N, through N_2 fixation, from the shade trees in coffee and cacao plantations. Studies in other agroforestry systems (Rao et al., this volume) have also shown the limited contribution of N_2 fixation by trees to the current associated crops, and suggest that the importance of this characteristic has been over-emphasized. The ability of a shade species to produce large quantities of organic material, as litter and pruning residues, can be more important than N_2 fixation because of the positive effects on soil chemical and physical properties, especially in plantations that are fertilized (Beer, 1988).

Nutrient cycling

Most aspects of nutrient cycling will be directly affected by the choice of shade species since these species differ significantly in aboveground biomass productivity, rate of biomass decomposition and fine root biomass productivity (Palm, 1995). They may also differ in rooting depth though in the humid tropics, where most coffee and cacao plantations are found, the majority of the roots will be found near the soil surface. Cuenca et al. (1983) reported that coffee roots were infected with vesicular arbuscular mycorrhizae and that these mycorrhizal-fine root associations invaded the litter layer, resulting in micro-stratification of coffee and tree roots (Herrera et al., 1987).

A comparison of Ca and Mg in the stems and branches of unpruned non-leguminous *C. alliodora* and pruned leguminous *E. poeppigiana* found greater accumulations of these nutrients in *C. alliodora*. However, transfer of N, P, K, Ca and Mg to the soil was greater from *E. poeppigiana* (Fassbender, 1993). Working in the same plots, Muñoz (1993) found that the combined fine roots in the *E. poeppigiana*-cacao association decomposed more quickly than the leaves of either species. Although total biomass and nutrients were greater in leaf litter, he pointed out that the more rapid turnover of smaller amounts of nutrients in fine roots within the rhizospere may be of considerable ecological significance. A higher total nutrient content was found in the *C. alliodora* associations (Alpizar et al., 1986), which had a greater biomass of fine roots than the *E. poeppigiana* associations (Fassbender, 1993; Muñoz, 1993). Greater leaching losses of Ca and Mg occurred in these *E. poeppigiana* associations (Imbach et al., 1989a; 1989b) possibly because the return of nutrients to the soil surface was concentrated in green (pruned) biomass which decomposed rapidly (Heuveldop et al., 1985). Despite the greater nutrient losses, cycling indices (relation of nutrient turnover to nutrients in the biomass) were higher in the pruned *E. poeppigiana* association (Beer et al., 1990; Nair et al., 1995).

Transfer of N_2 fixed or extracted from the soil by leguminous shade trees to the non-N_2-fixing associated crop has generally been assumed to occur largely through the aboveground pruning residues and litterfall (e.g., Fassbender, 1993). Studies carried out in Latin American coffee and cacao plantations, with 120–560 leguminous shade trees per hectare (0–3 pollardings per year), showed that these inputs can vary from 3–14 Mg ha^{-1} yr^{-1} of dry matter containing 60–340 kg N ha^{-1} yr^{-1} (Beer, 1988). Escalante et al. (1984) calculated that 57–66 kg N ha^{-1} yr^{-1} was released through nodule senescence and decomposition of unpruned *E. poeppigiana* with no difference in nodule N content (22–23 kg N ha^{-1}) between fertilized and unfertilized plots. Nygren and Ramírez (1995) found a turnover of 6.8 to 35.4 g N tree^{-1} in a 23-week pruning cycle (9.6 to 50.0 kg N ha^{-1} yr^{-1}) through *E. poeppigiana* nodule senescence and decomposition. These two studies suggest that a significant proportion of N_2 fixed by shade trees may be transferred below ground to non-N_2-fixing plants.

Babbar and Zak (1994, 1995) found higher rates of N mineralization in Costa Rican coffee plantations shaded by *E. poeppigiana* (148 kg N ha^{-1} yr^{-1}) compared to unshaded plantations (111 kg N ha^{-1} yr^{-1}). Both were heavily fertilized with mineral N at rates up to 300 kg N ha^{-1} yr^{-1}. They concluded that N cycling was more efficient in shaded plantations because, despite the greater availability of mineralized N, less N was lost through leaching.

Shade management, especially pruning, has a critical influence on nutrient cycling and, hence, in addition to its use in managing the microclimate of the underlying crop, provides a tool to manipulate the timing and quantity of nutrient transfer from tree to soil. Although some information exists on the belowground processes of these systems (see above), this stratum is still a 'black box' whose internal biological and chemical mechanisms are poorly quantified and little understood.

Soil erosion

Runoff and soil loss are lower in shaded than in unshaded plantations (Bermudez, 1980; Wiersum, 1984; Leon, 1990). However, similar benefits can be obtained through mulching without shade (Willey, 1975). If shade trees are to contribute to erosion control, natural litterfall and/or pruning residues should maintain a mulch layer during the rainy season. In this respect, slow litter decomposition would be an advantage.

A dense shade canopy will provide better soil protection than an open canopy during high intensity rainfall. Trees, however, can also adversely redistribute precipitation. For example, during low- to moderate-intensity rainfall, coalescence and drip from the leaves of tall timber trees can loosen soil particles and increase soil surface erosion (Wiersum, 1984). Hence, a low crown with small leaves is preferable to reduce drip damage.

Greenhouse gases

In heavily fertilized (including 300 kg N ha^{-1} yr^{-1}) Andisols from shaded and unshaded Costa Rican coffee plantations, laboratory incubation showed higher rates of total denitrification in soil from the shaded plantations (732 vs 455 μg N_2O–N kg^{-1} d^{-1}, respectively) (Babbar and Zak, 1995). Thus, it appears that the use of shade trees in fertilized plantations may contribute to greenhouse gases. It is unlikely, however, that such high denitrification rates, the highest of which was equivalent to approximately 10 kg ha^{-1} day^{-1}, will occur in the field for any prolonged period.

Kursten and Burschel (1993) calculated that 14–52 Mg C ha^{-1} are stored in the aboveground woody biomass of shade trees in coffee and cacao plantations. Compared to annual crops, these agroforestry systems also stored an additional 10–50 Mg C ha^{-1} in the litter layer and soil organic matter. However, the most valuable potential contribution of shaded perennial systems, with respect to atmospheric CO_2 levels, lies in the protection of the remaining forest by offering farmers on the agricultural frontier a sustainable cash-crop alternative to slash-and-burn cultivation for annual crops. This could prevent the release of up to 1000 Mg C ha^{-1}.

Environmental contamination

Besides its undesirable contribution to greenhouse gases and global warming (Duxbury et al., 1993), fertilizer N can pollute groundwaters with nitrite and nitrate. Groundwater NO_3–N concentrations in the Central Valley of Costa Rica, where 50% of the groundwater recharge area is under intensive coffee management with little or no shade, occasionally exceed the 10 mg L^{-1} (Reynolds, 1991) considered to constitute a human health hazard (Frazer et al., 1980). Annual leaching losses at 60 or 100 cm depth were 5 to 9 kg N ha^{-1} in shaded and 24 kg N ha^{-1} in unshaded coffee plantations (Imbach et al., 1989a; Babbar and Zak, 1995), both of which were much lower than the 50 to 100 kg N ha^{-1} yr^{-1} that is typical for tropical agroecosystems (Imbach et al., 1989b). Thus, adding shade trees has the potential to reduce nitrate contamination of groundwater in areas of intensive coffee management. The need to reduce contamination of the environment by pesticides, which are heavily used in high-input coffee and cacao monocultures (Willey, 1975; Graaff, 1986), provides another argument for maintaining shade trees (Boyce et al., 1994).

Light availability

Quantitative data about the level of shading in coffee and cacao plantations are often lacking or are difficult to compare since they have been measured using different light sensors and methodologies (e.g., for cacao, Murray, 1954; Vernon, 1967; Bonaparte, 1975; Luján, 1992). In addition to modifying light availability, tree canopies also negatively affect light quality (Nair, 1979; Bainbridge et al., 1996). The upper limit of acceptable shade for coffee (a C3 plant) is considered to be between 40% and 70% (Kumar and Tieszen, 1980; ICAFE, 1989b; Muschler, 1995). A similar range may apply for cacao (Alvim, 1977). For both crops, nutrient and/or moisture limitations increase the degree of shading needed.

The effects of modifying light availability are determined by the specific requirements of each crop, which vary with age and site conditions, particularly with soil fertility (Willey, 1975). Photosynthetic rates of coffee are at a maximum at intermediate shade levels in many of the climatic conditions found in the tropics (Nutman, 1937a; 1937b). While saturating light levels were as low as 300 $\mu mol\ m^{-2}\ s^{-1}$ for shaded coffee, the level for unshaded plants was as high as 600 $\mu mol\ m^{-2}\ s^{-1}$ (Kumar and Tieszen, 1980). The reduced photosynthetic rate that occurred above these radiation levels was explained as a reaction to leaf temperatures above 25 °C, a condition to which coffee is very sensitive (Maestri and Barros, 1977). However, these measurements were made on individual leaves or isolated plants, which do not represent the conditions that affect most of the coffee foliage in an unshaded, high density plantation, where self-shading is considerable (Willey, 1975).

Temperature, wind speed and humidity

Temperatures of exposed coffee leaves can exceed 40 °C (Maestri and Barros, 1977). In a Mexican coffee plantation under the shade of *Inga jinicuil* (205 trees ha^{-1}; average tree height 14 m), average maximum temperature was reduced by 5.4 °C, average minimum temperature was increased by 1.5 °C, and the vapor pressure deficit was substantially reduced, compared to unshaded plantations (Barradas and Fanjul, 1986). In East African coffee plantations shaded by tall *Paraserianthes falcataria* (syn. *Albizia moluccana*, *A. falcataria*) trees, temperatures were 5–6 °C lower and humidity variations were greater than in unshaded sites (Kirkpatrick, 1935). Reduced heat-load of the coffee plants during the daytime and reduced heat losses at night explain this buffering effect. The inclusion of shade trees also reduces wind speed in the crop strata (Schroeder, 1951; Alvim, 1977). This is of particular importance for young cacao plants which are highly susceptible to desiccation (Leite et al., 1981). Nevertheless, since coffee is planted over a wider climatic range than cacao, the importance of these microclimatic effects may be greater for coffee.

Crop phenology, yields and quality

When nutrient availability is not limiting growth, a positive correlation between cacao yields and light availability has been reported (Murray, 1954; Bonaparte, 1975). Vernon (1967b) concluded that the relationship between cacao yields and available light was approximately linear in the range of 30% to 60% of full sunlight. However, when modelling the complete range from 0 to 100%, a quadratic model gave a better fit than the simple linear model, suggesting that some degree of shading for cacao is desirable. Note that photosynthetically active radiation (PAR) was not measured in any of the studies cited in this paragraph.

Cannell (1975) suggested that close spacing of coffee bushes results in mutual shading that may inhibit floral initiation at existing nodes on coffee branches. Castillo and López (1966) and Jaramillo and Valencia (1980) reported fewer coffee flowers under shade than in full sunlight. Using artificial shade treatments, Montoya et al. (1961) and Castillo and López (1966) found significant increases in the number of nodes per coffee branch and flower buds per node as sunlight levels increased. Montoya et al. (1961) also reported a significant positive correlation between the increases in the number of nodes per branch and yields per bush the following year. Cannell (1975) stated that the most important component of yield is the number of nodes formed. Therefore, it seems logical to conclude that, because the number of nodes formed and the number of fruit set at each node can both be affected by light levels, shading on good sites can directly reduce coffee yields even when all other growth factors are favorable. Using multiple regression analysis, Beer (1992) detected such a direct negative effect of increased shade tree density on coffee berry production, in addition to the indirect effect on yield associated with reduced bush growth.

Lagemann and Heuveldop, (1983) reported that higher shade density had a negative effect on coffee yield. Unshaded, high-input coffee can yield more than shaded plantations with the same management (Fournier, 1988; Chamorro et al., 1994). Nevertheless, in some trials in Costa Rica, production of the varieties Bourbon and Caturra under biannually pollarded *E. poeppigiana* was equal to or even greater than production from unshaded coffee that had been given the same management (ICAFE, 1989a; Ramírez, 1993). Machado (1959), working in Columbia, found yield advantages for *Coffea arabica* var. Típica shaded by *Inga* spp., as compared to unshaded coffee (20% higher yields in fertilized plots and over 60% higher in unfertilized plots). However, shading by *Calliandra* spp. reduced the yield by about 30% compared to the unshaded plots. In another experiment (Machado, 1959), production of the unshaded treatments for var. Bourbon, and also to a much lesser degree for var. Típica, exceeded the shade treatments, especially in fertilized plots, but the advantage of the unshaded plots diminished from year to year.

Thus, some studies have demonstrated that higher yields can be obtained from intensively managed unshaded coffee but the results are inconsistent, probably because of widely varying site conditions and management. When comparing shade versus no-shade, or comparing different shade species in on-farm applied research, a group of factors vary rather than just the factor ‘species.’ In each treatment, optimal management should be used. This implies different coffee/cacao and shade tree planting densities, pruning, fertilization and other agrochemical applications, in order to judge the potential of each shade species and/or management without shade (Somarriba et al., 1996).

The outcome of adding shade trees to coffee or cacao plantations depends on many factors, the most important of which are related to the following influences: (1) production objective(s), (2) inputs available, and (3) environmental characteristics (Muschler, 1997, 1997). While the factors in groups 1 and 2 can easily be altered, environmental characteristics, such as soil properties, water availability or elevation, permit limited or no changes at all. Hence these latter factors may be more critical in determining the shade response in different plantations. Figure 1 is an attempt to reconcile seemingly contradictory shade responses of coffee by considering them according to environments. This figure is hypothetical, but data from long-term experiments in different environments fit this model well (R. Muschler, 1997, unpublished data).

When coffee production is plotted against elevation, for soils with and without nutrient and/or moisture limitations, the highest production of unshaded coffee typically occurs within the range between 900 and 1200 m.a.s.l. Actual values for each region depend on the site-specific climatic conditions, including the effects of latitude on average temperatures. At lower elevations, unshaded coffee production decreases strongly in response to high temperatures, while at higher elevations it decreases in response to low temperatures, and possibly wind damage. Under these sub-optimal conditions, trees can buffer the microclimatic extremes and can increase coffee production over that of unshaded sites (‘shade contribution’). However, shading of coffee in the optimal elevation range results in a yield depression. On soils with nutrient or water storage limitations at all elevations, the potential yield advantage of unshaded versus shaded coffee is reduced or even reversed; i.e., the relative proportion of the shade contribution increases on sites with these soil limitations (Figure 1B).

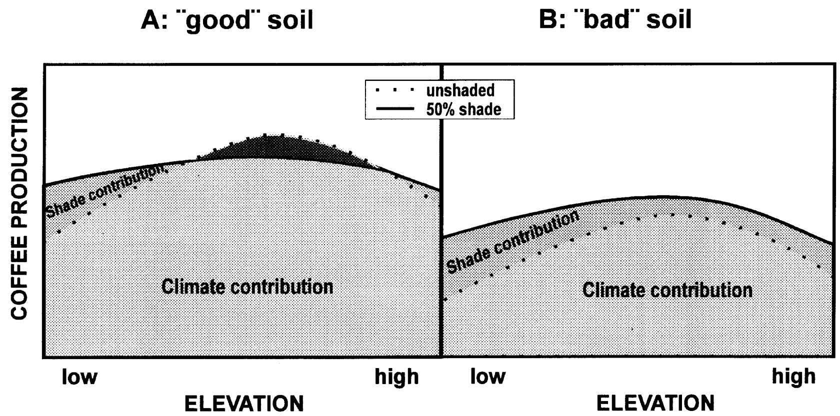

Fig. 1. Idealized hypothetical coffee production without shade and under trees giving 50% shade as a function of elevation for soils without (A) or with (B) limitations of rooting depth, nutrients or moisture. While production of unshaded coffee for given soil conditions and elevation depends primarily on climatic conditions ('Climatic contribution'), shade may improve production ('Shade contribution') in marginal conditions. At ideal coffee elevations and on soils without limitations, shading may reduce production (dark area) (modified from Muschler, 1997).

Despite the common belief that coffee produced under shade is of higher quality, Willey (1975) points out that although light attenuation may cause etiolation and changes in leaf morphology, it has little effect on the morphology and hence the chemical constituents of fruits. He therefore concludes that shade will affect the quality of a vegetative product, such as tea, but that quality effects on cocoa or coffee beans are unlikely to be significant. Hernández (1995) reported insignificant differences between cherry or bean sizes from shade and no-shade coffee plots. However, during two consecutive years, the conversion factor for dried beans per unit weight of green cherries was 0.6% higher under shade, which translated into an additional 44 kg ha^{-1} of processed coffee at average Costa Rican production levels. Guyot et al. (1996) demonstrated that shade and altitude have similar significant positive effects on coffee bean size and the chemical parameters which determine quality because they slow ripening.

The effects of shade on coffee and cocoa yields are difficult to characterize since the premise of 'proper shade management and design' is seldom assured. Furthermore, the relative yield advantage of unshaded coffee or cacao may be limited: (1) to 'ideal' soil and climatic conditions (Figure 1); (2) to one or two decades of production, after which environmental degradation, especially via soil erosion and pesticide residues, may seriously reduce productivity and/or environmental quality (Boyce et al., 1994); and (3) to frequently replanted and pruned plantations since unshaded coffee or cacao bushes have a shorter life expectancy than shaded bushes (Ahenkorah et al., 1974; Wrigley, 1988).

Pests and diseases

Black pod (*Phythphora palmivora*) disease of cacao is reported to be favored by increased humidity due to increased shading (Dakwa, 1980; Smith, 1981). Comparing microclimatic conditions, spore liberation and the incidence of the pod disease *Moniliophthora roreri* in cacao under the shade species *E. poeppigiana*, *G. sepium* or *I. edulis*, Meléndez (1993) did not find significant differences except for higher spore counts underneath *E. poeppigiana*. This, however, did not correlate with a higher disease incidence, presumably due to the absence of other factors which favor pod infection.

Excessive shade increases the incidence of other economically important fungal diseases (e.g., *Mycena citricolor* in coffee) (ICAFE, 1989b), especially in very moist situations such as river sides or valley bottoms. In contrast, damage caused by *Cercospora coffeicola*, a fungus disease which can completely defoliate coffee plants, is greater in unshaded plantations (Nataraj and Subramanian, 1975), possibly due to the higher susceptibility of water-stressed or nutrient-deficient plants (Wrigley, 1988). The provision of more or less shade to help control these diseases must seek a balance since they occur together in many plantations. While these generalizations are valid for *M. citricolor* and *C. coffeicola* on most if not all sites, the correlation between the level of shade and the incidence of *Hemileia vastatrix* seems much weaker (Eskes, 1982). This coffee leaf rust causes serious defoliation both in unshaded and shaded conditions. Shade trees can also act as alternative hosts, and hence as sources of inoculum, for crop diseases. For example, *Inga* spp. and many fruit trees – such as oranges and mangos – may be infected by *M. citricolor* (Wellman, 1961).

The coffee berry borer (*Hypothenemus hampei*) is reported to be favored by dense shade (Fonseca, 1939; Wrigley, 1988) but it has been suggested (B. Medina, 1997, pers. comm.) that some shade favors the persistence of the biological control agents *Beauveria bassiana*, an entompathogenic fungus, and *Cephalonomia stephanoderis*, a parasitic wasp. On the other hand, mealybug (Homoptera) infestations (Campbell, 1984) and Anthracnosis fungal disease (*Colletotrichum gloeosporioides*) of unshaded cacao (Porras and Sánchez, 1991) are two of the reasons why cacao monocultures are not economically justified despite the initial production advantage (Ahenkorah et al., 1974).

Weeds

The proper selection and management of permanent shade species can reduce labor input and weeding costs considerably (Silva et al., 1990). These can amount to 70% of all costs during the first two to three years of a cacao plantation (Corven, 1993). Shade can shift species composition towards less aggressive weeds (e.g., more broadleaf, less Gramineae) (Vernon, 1967a; Huxley, 1975), a change of considerable economic importance even if total weed biomass were unaffected. After removing shade trees and thinning coffee plants, weed biomass increased almost tenfold to > 12 Mg ha^{-1} (dry weight), with a higher incidence of the more light-demanding aggressive graminaceous weeds (Goldberg and Kigel, 1986). Weed growth in a coffee plantation was virtually eliminated and grassy weeds completely suppressed under a ≥ 40% homogeneous shade treatment (Muschler, 1997). The savings that resulted from not having to weed (2.5%–3% of total production costs in mature plantations) were double the costs of managing shade trees that are pollarded twice per year (Rojas Cubero, 1996). This is one of the reasons why Costa Rican coffee farmers plant more leguminous shade trees when coffee prices are low.

Buffer zone agroforestry and conservation of biodiversity

In terms of their architecture and ecology, many traditional shaded coffee and cacao plantations (which often have a diverse shade component that includes > 50 tree species (Espinoza, 1985)) resemble natural forest more than most other agricultural systems. Shaded coffee plantations in Mexico compare quite favorably to natural forest as refuges for migratory birds (Wille, 1994; Greenberg et al., in press). These agroforestry systems also have a high potential as refuges for biodiversity, particularly in deforested areas (Young, 1994; Perfecto et al., 1996), and for buffer zone management. Moreover, they can serve as pathways or stopovers for the migration of animal species between natural reserves. When native species are used as shade trees in a buffer zone, a larger gene pool of these species can be maintained than would be possible in the protected area alone.

Productivity of shade trees

Timber-producing shade trees have low management costs (Calvo and Platen, 1996) and are considered a ‘saving account’ that can be realized at times of low prices or failure of the underlying crop (Rodríguez, 1982; Mussak and Laarman, 1989; Barker, 1991; Somarriba, 1992). Income from fruit trees, timber or firewood, and other perennial crops used as shade for coffee or cacao is significant (Sabogal, 1983; Kajomulo-Tibaijuka, 1985; O’kting’ati and Mongi, 1986; Escalante et al., 1987) and may result in better financial performance than would occur in plantations using conventional, leguminous, ‘service’ shade trees (Glover, 1981; Platen, 1993; Hernández and Platen, 1995; Trejos and Platen, 1995).

Timber production

A conservative estimate of the merchantable timber increment from 100 trees ha^{-1} of *C. alliodora* in a coffee plantation is 4–6 m^3 ha^{-1} yr^{-1} (Table 2). Assuming high coffee prices and an average coffee production of 30 ‘fanegas’

Table 2. Timber production from Costa Rican and Colombian coffee plantations.

Species	Place	Elevation (m.a.s.l.)	Rainfall (mm/yr)	Tree density (#/ha)	MAI Vtot[a] (m^3 ha^{-1} yr^{-1})	MAI Vcom[b] (m^3 ha^{-1} yr^{-1})	Reference
Cordia alliodora	CATIE	550	2600	228	13		Rosero and Gewald (1979)
Cordia alliodora	Costa Rica	50–750	> 2600	68–290		6–13	Somarriba and Beer (1987)
Cordia alliodora	Colombia	1200–1800	–	170		4	Escobar (1979)
Cordia alliodora	CATIE	600	2600	139	13		Heuveldop et al. (1985)
Cordia alliodora	La Suiza, CR	600	2600	117–275	7–12		Beer et al. (1981)
Cordia alliodora	CATIE	600	2600	110–350	10–15		Hernández (1995)
Cordia alliodora	Turrialba	600–800	2600	50–150		1.5–2.5	Barker (1991)
Cordia alliodora	Colombia	1300	2475	100		4–5	Chamorro et al. (1994)
Cordia alliodora	Turrialba	600	2600	120–410		4–20	González (1980)
Cordia alliodora	Turrialba	600	2600	120–290		6–15	Somarriba (1990)
Eucalyptus grandis	Turrialba	500–1400	2600	1000	2–26		Salas (1994)
Eucalyptus grandis	Turrialba	500–1400	2600	950	1.5–32.5		Salas (1994)
Cedrela odorata	Puriscal, CR	800	2500	78+141		7–12	Ford (1979)
Cedrela odorata	Sn Carlos, CR	250	4100	84		8.3	Ford (1979)
Cedrela odorata	Puriscal, CR	800	2500	32–87		3–4.5	Sabogal (1983)
Cedrela odorata	Puriscal, CR	1000–1100	2200	150–290		0.9–3.1	Espinoza (1985)

[a] Mean annual increment (MAI) of total stem volume.
[b] Mean annual increment of commercial wood volume. For *C. alliodora* it is 64% of Vtot (Somarriba and Beer, 1987).
CR = Costa Rica.
#/ha = Number of trees per hectare.

ha^{-1} yr^{-1} (see Table 3 for explanation), the value of the timber increment could compensate for a reduction of coffee yield of up to 17%. For intermediate prices, timber value could compensate for yield reductions of up to 33%, while at low coffee prices – which generate a profit of less than US$5 per fanega – the value of the timber can compensate for the loss of all the coffee production. Of course, this crude comparison does not take into account discounting, tree management costs (including felling damage (Somarriba, 1992)) and other factors that affect the financial comparison of coffee production with and without the timber trees (Hernández, 1995). Moreover, the coffee revenue is generated immediately while revenue from timber, though substantial, is available only at the end of the rotation.

The above contrasts are based on conservative estimates of the relative values of coffee and timber since timber prices are likely to increase in the future (Gómez, 1995) while prolonged coffee price increases are unlikely. The recent interest of Central American coffee institutions in sustainable management (PROMECAFE, 1995), including the use of timber-producing shade trees, is partly due to these trends. Diversification and new markets, such as specialty coffees and organic coffee, may be the only options for farmers to increase their income from perennial crop plantations. The above studies of timber production in coffee plantations were mostly carried out at lower altitudes and in areas with relatively high rainfall (Table 2). These are the zones where this practice has the most potential since the duration of timber rotations and competition for water between these unpruned trees and underlying crops are minimized.

Damage of coffee/cacao during the harvest of intermixed timber trees is a major concern of many farmers. This is particularly true in the case of cacao, which forms a more permanent structure than coffee and is, therefore, slower to recover from physical damage. Felling of 29 mature *C. alliodora* in coffee plantations in the tropical humid zone of Turrialba, Costa Rica affected 498

Table 3. Comparison of the values[a] of coffee production and potential annual increment of *Cordia alliodora* (100 trees ha^{-1}) in a Costa Rican coffee plantation.

Price paid for fresh coffee before pulping (US-$/fan) (1)		Production cost per fanega[b] (US-$) (2)	Profit from sale of one fanega of coffee (US-$) [(1) – (2)] = (3)	Value of annual timber increment (US-$) (4)	Number of fanegas of coffee equivalent to timber value [(4) – (3)] = (5)
High	75	45[c]	30	150	5
Intermediate	60	45	15	150	10
Low	< 50	45	< 5	150	> 30

[a] Prices for December 1995 converted to US-$ @ 200 Colones/US-$. A mean annual increment of 4 m^3 ha^{-1} yr^{-1} of merchantable timber of *Cordia alliodora* is assumed (Table 2).
[b] 1 fanega = 256 kg of fresh coffee berries.
[c] 9000 Colones is a low estimate, considering that Rojas (1996) gives a cost of 15,500 Colones for producing one fanega.

coffee plants but most (91%) were only slightly damaged, principally by the tree crowns (Somarriba, 1992). Thus, tree crown dimensions and characteristics are important criteria when considering possible timber harvesting damage in perennial crop plantations. Log skidding was a minor source of damage. Damage to crops, and the consequences of this damage, can be reduced by felling during periods of low coffee prices or yields, felling immediately after the harvest but prior to annual coffee pruning when some of the damage can be repaired, and by planting the trees between the rows of coffee, along roads and on plantation borders. Despite possible crop damage, the low restoration costs of affected plants, the small reductions in coffee yields, and the large financial gain from timber sales strongly support the use of timber trees in coffee plantations.

Fruits and fuelwood production

In a comparison of unshaded coffee with mixed plantations, which included oranges and the timber tree *Cedrela odorata*, Espinoza and Hidalgo (1991) found that all economic indicators favored the diversified systems. However, market limitations greatly restrict the commercial potential of fruit trees in many regions. Bananas (*Musa* spp.), which are often used as temporary shade and are sometimes a permanent component of plantations, compete strongly with coffee (Robinson, 1961; Mitchell, 1963). Furthermore, during harvest or because of windfall, banana stems may damage underlying crops and newly established permanent shade trees. The priorities of the farmers and availability of markets need to be verified before promoting the use of fruit trees as shade for coffee or cacao.

Shade trees in coffee plantations can produce large quantities of high-quality fuelwood: e.g., 36.5, 8.3 and 8.8 m^3 ha^{-1} yr^{-1} from 635 trees ha^{-1} of *Mimosa scabrella* (Picado, 1985), 1250 trees ha^{-1} of *Inga densiflora* (Salazar, 1985) and 330 trees ha^{-1} of *Gliricidia sepium* (Salazar, 1984), respectively. The fuelwood obtained from coffee pruning and renewal is also an important resource for many rural families.

Future research priorities

So far, ecological research on shade trees in coffee and cacao plantations has emphasized: (1) effects of shade-soil fertility interactions on coffee/cacao production; (2) shade-microclimate-pest/pathogen interactions; and (3) nutrient cycling, soil fertility maintenance and sustainability issues. Applied research has focused principally on species selection, propagation methods, determination of optimal population densities, planting arrangements and pruning practices. The aim has been to intensify coffee/cacao management, in comparison with traditional shaded systems, for higher yields and economic returns. A wealth of site- and/or species-specific data exists on crop productivity under shade and on many of the underlying physiological changes and processes in both crop and tree, as well as the effects of shade trees on microclimate and soils. It is therefore valid to ask what further biophysical research on this system should be a priority. Before this question can be answered, it is necessary to examine the justifications for further research and to identify the people it should benefit.

A number of factors, both economic and environmental, support the claim that improved management of shade trees in perennial crop systems is still a priority topic. There is increasing demand and willingness of consumers to pay premium prices for export crops that are sustainably and/or organically produced, controlled in some cases by certification requirements (Boyce et al., 1994; Revista Forestal Centro-Americano, 1996). Carbon sequestration by tropical forests and agroforestry systems (Kursten and Burschel, 1993) is another option which can be ‘sold’ to developed countries (Dixon, 1995). These international influences, together with internal pressures in the producing countries to protect watersheds and biodiversity, reduce environmental contamination and diversify insecure monocropping economies, have changed the high-input ‘green revolution’ approach of the national coffee institutes of Central America (PROMECAFE, 1995). Nevertheless, the rate of adoption of diversified sustainable technologies is slowed by the conspicuous absence of clear guidelines on how to select and manage appropriate shade trees for different sites in order to augment the advantages of tree-crop associations, while minimizing the disadvantages. Shade tree selection criteria (Beer, 1987) and management recommendations (e.g., desirable light levels) are often based on empirical observation rather than on objective quantification with control of confounding factors (Sanchez, 1995). Future research should integrate and supplement the existing results in order to provide a comprehensive understanding of the processes occurring within and between the components in shaded perennial crop plantations, thereby permitting the extrapolation of the site- and/or species-specific results. Only then can generalized recommendations (e.g., using decision support tools such as expert systems) be provided as a framework for validation in the varying biophysical and socioeconomic circumstances where coffee and cacao are produced.

The following sections cover, in order of decreasing priority, three ecological research areas of particular concern to the national organizations. We do not attempt to specifically discuss the socioeconomic priorities which are equally important to farmers. Related applied research topics are then discussed in the final section.

Competition between trees and crops

Basic studies are still required on the relative importance of competition for light, water and nutrients along ecological gradients, e.g., to identify the limiting factor(s) for a range of biophysical sites. Studies are needed on the effects of tree crown architecture and dynamics (phenological and/or pruning cycle), for different tree species and sizes, on the availability of photosynthetically active radiation for the understory crop (Somarriba et al., 1996). The effects of shade on crop phenology, particularly the initiation and development of flowers and fruits (Beer, 1992; Young, 1994), on coffee bean size, on the conversion factor bean/cherry and on coffee quality (taste studies) are related topics that need additional study since they have economically important implications (Hernández, 1995; Muschler, 1995).

Greater emphasis should be given to studies of belowground interactions, in part because there is a dearth of relevant information (Anderson and Sinclair, 1993). The influence of shade trees on water availability for the understory crop in seasonally dry zones is as important a research topic now as when Franco (1951) identified it as the main justification for eliminating shade trees from coffee plantations in many areas of Brazil. Competition for water can occur, even in tropical rain forest areas, during short dry periods (Kozlowski, 1982).

Information is available on seasonal nutrient uptake by coffee and cacao (Rodríguez et al., 1963; Carvajal et al., 1969) but not for the shade trees. Although considerable information is available on annual nutrient cycling totals and nutrient export in timber, fuelwood, and crop products (Fassbender, 1993), seasonal nutrient cycling patterns and hence competition are little understood. Decomposition patterns of fine roots and litter, and nutrient release, will affect the relative importance for crops of maintaining/increasing SOM (a medium- to long-term nutrient reserve) versus providing a nutrient flush (a short-term nutrient source) (Haggar et al., 1993). The effect of site conditions on the functioning of shade tree root associations with mycorrhiza or rhizobium (e.g., on N_2 fixation) is another research area that would facilitate fine tuning of management and the extrapolation of site-specific results. Little is known about the pathways and efficiency of nutrient uptake from organic residues produced in these systems, e.g., the role of different SOM fractions and micro-flora/fauna. In part, this is due to the difficulty in using tracers such as ^{15}N to study systems including large trees (Clinton and Mead, 1994). The interactions between inorganic and organic fertilizers should be studied to improve the efficiency of use of the former. Research has tended to concentrate on N when the supply of other nutrients may be more important: e.g., P in the volcanic P-fixing soils of Central America, and cations in the acid soils of many humid tropical areas. Studies of fine root dynamics could permit matching fertilization timetables to periods of fine root growth of crops when the trees are less competitive (Muñoz, 1993). Fertilizer distribution and potential root barrier species, such as some Gramineae, should be tested as a means to manage the spatial distribution of coffee and tree roots (Schroth, 1995), at least during the juvenile phase.

Coffee pests and diseases

There is a lack of agreement among farmers and scientists as to whether shade trees reduce or increase diseases and pests of economic importance, such as leaf rust (*H. vastatrix*) and the coffee berry borer (*Hypothenemus hampei*). Further research is needed to understand how shade trees modify the microclimate to the detriment or benefit of these diseases and pests, and hence on their epidemiology. For example, many coffee farmers believe that the higher incidence of *M. citricolor* under shade is related to rain drip from upperstory tree leaves, particularly with timber species whose height can not be regulated by pruning; this is a topic that requires testing. The trade-off between competition with the crop and the value of shade to control weed biomass and to favor less competitive weed species merits further study. The effect of different shade management options (including no-shade) on soil pests of coffee and cacao, such as nematodes, is another area of research with immediate economically important applications. In general, the role of shade trees in integrated pest management for coffee is an increasingly important research area.

Sustainability and environmental benefits

Many coffee farmers and their organizations have demonstrated that they are concerned about medium- to long-term perspectives by implementing erosion control recommendations and ignoring advice to eliminate shade trees. However, they generally lack solid information about the factors which control sustainability and environmental effects, aspects which they are increasingly pressured to consider and which can offer them marketing advantages (e.g., certification). Subjects that require field study in commercial and experimental plantations include the medium- to long-term trends in total and available macronutrients, SOM (total and fractions), soil structure, the hydrological regime (infiltration vs run-off, internal drainage, water-holding capacity), leaching, ground water quality, and soil erosion (surface erosion and superficial soil slippage). Further work is needed to quantify the ability of these agroforestry systems to capture CO_2 (e.g., by increasing SOM), or to reduce the emissions by providing a sustainable agricultural alternative to slash and burn (probably more relevant in the case of cacao than coffee).

Applied research

Applied research, drawing on the process-oriented research discussed above, should emphasize silvicultural interventions to reduce competition, reduce crop pests and diseases and address environmental problems. Topics include regional selection trials and criteria for shade species/varieties/provenances based on root architecture as well as aboveground structural characteristics; the effects of tree establishment methods on rooting patterns (Schlönvoigt, 1993); and spacing, thinning and pruning regimes (Somarriba et al., 1996). Studies of the potential of tree mulch, produced on- or off-site, to substitute for inorganic fertilizer will have increasing importance due to the rapid growth in demand for "organic" products. Despite the above emphasis on crop production, the need for research to improve the productivity of the tree component should not be forgotten, e.g., adaptation of plantation silviculture to improve management of widely spaced timber trees in perennial crop plantations. Many of the principles that have been illustrated above could be applied to improve combinations of upperstory trees with other perennial crops, such as those mentioned in the introduction.

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