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REVIEW

Multifunctional shade-tree management in tropical agroforestry landscapes – a review

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Summary

1. Agricultural intensification reduces ecological resilience of land-use systems, whereas paradoxically, environmental change and climate extremes require a higher response capacity than ever. Adaptation strategies to environmental change include maintenance of shade trees in tropical agroforestry, but conversion of shaded to unshaded systems is common practice to increase short-term yield.

2. In this paper, we review the short-term and long-term ecological benefits of shade trees in coffee *Coffea arabica, C. canephora* and cacao *Theobroma cacao* agroforestry and emphasize the poorly understood, multifunctional role of shade trees for farmers and conservation alike.

3. Both coffee and cacao are tropical understorey plants. Shade trees in agroforestry enhance functional biodiversity, carbon sequestration, soil fertility, drought resistance as well as weed and biological pest control. However, shade is needed for young cacao trees only and is less important in older cacao plantations. This changing response to shade regime with cacao plantation age often results in a transient role for shade and associated biodiversity in agroforestry.

4. Abandonment of old, unshaded cacao in favour of planting young cacao in new, thinned forest sites can be named 'short-term cacao boom-and-bust cycle', which counteracts tropical forest conservation. In a 'long-term cacao boom-and-bust cycle', cacao boom can be followed by cacao bust due to unmanageable pest and pathogen levels (e.g. in Brazil and Malaysia). Higher pest densities can result from physiological stress in unshaded cacao and from the larger cacao area planted. Risk-averse farmers avoid long-term vulnerability of their agroforestry systems by keeping shade as an insurance against insect pest outbreaks, whereas yield-maximizing farmers reduce shade and aim at short-term monetary benefits.

5. *Synthesis and applications*. Sustainable agroforestry management needs to conserve or create a diverse layer of multi-purpose shade trees that can be pruned rather than removed when crops mature. Incentives from payment-for-ecosystem services and certification schemes encourage farmers to keep high to medium shade tree cover. Reducing pesticide spraying protects functional

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agrobiodiversity such as antagonists of pests and diseases, pollinating midges determining cacao yields and pollinating bees enhancing coffee yield. In a landscape perspective, natural forest alongside agroforestry allows noncrop-crop spillover of a diversity of functionally important organisms. Knowledge transfer between farmers, agronomists and ecologists in a participatory approach helps to encourage a shade management regime that balances economic and ecological needs and provides a 'diversified food-and-cash crop' livelihood strategy.

Key-words: agricultural intensification, Arabica and Robusta coffee, boom-and-bust cycles, cacao yield, ecological-economic trade-offs, ecological resilience, functional biodiversity, household vulnerability

Introduction

Conversion of tropical forest and agricultural intensification are the most important drivers of tropical biodiversity loss and associated ecosystem services (Foley *et al.* 2005). It is a paradox that agricultural intensification at local and landscape scales tends to make land-use systems less resilient and more vulnerable to disturbances, at a time when environmental change and climate extremes call for a higher response capacity than ever. Ecosystem services arising from natural forests or from forest-like agricultural systems are usually not fully captured by the market, giving rise to the illusion that their economic value equals their market price, which is zero (Steffan-Dewenter *et al.* 2007; Verchot *et al.* 2007; Lin, Perfecto & Vandermeer 2008).

In many tropical landscapes, agroforestry systems (i.e. managing trees in addition to crops) are the major ecosystems that resemble natural forest (Schroth *et al.* 2004; Perfecto *et al.* 2007; Schroth & Harvey 2007; Bhagwat *et al.* 2008). As these systems potentially have high biodiversity conservation value, protection of pristine habitat needs to be combined with such environmentally friendly and sustainable land-use systems. Agroforestry systems enhance both rural livelihood and biodiversity conservation (Perfecto *et al.* 2007) and can mitigate changes in temperature and precipitation (Lin, Perfecto & Vandermeer 2008). Coffee and cacao, together the largest legal international trade volume beside petroleum (Donald 2004; Table 1), are the crops most commonly grown under shade trees to reduce physiological stress affecting longevity (Beer *et al.* 1998). Even though moderate shade levels have little effect on cacao or coffee yield (Wood & Lass 2001; Perfecto *et al.* 2005), farmers in many parts of the world are converting shaded cacao and coffee systems into unshaded monocultures to increase short-term income (Rice & Greenberg 2000; Siebert

Table 1. Comparing features of cacao and coffee agroforestry (References: see Table S1; Supporting Information)

	Cocoa *Theobroma cacao*	Coffee Arabica *Coffea arabica*	Coffee Robusta *Coffea canephora*
Original habitat	Understorey of tropical South American rainforests	Understorey of highland forests of SW Ethiopia and SE Sudan	Understorey of subsaharan African rainforests
Optimal altitude	0–400 (–1200)	1000–2000 m	0–700 m
Conservation value of plantations	Variable, but can be high. Tend to decrease over time through shade tree removal	Variable, but often high due to shaded agroforestry	Mostly low (reduced shade) but there are exceptions
Pollinator groups	Midges	Bees	Bees
Pollination dependency	100% pollination dependent	Self-pollinating, but pollination increases yield up to 50% (short-term flowering after rain)	Requires out-crossing with bees increasing yield by 90% (irregular flowering)
Pest and disease problems (caffeine content given as a measure of insect deterrence)	High	High (0·8–1·4%)	Less than *C. arabica*, resistant to e.g. coffee leaf rust (1·7–4·0%)
No. of conservation studies (shaded agroforestry)	602 (77)	252 (32) [coffee in general: 1275 (142)]	111 (7) [coffee in general: 1275 (142)]
Global production 2008 [million t]	4·3	6·2–6·6	2·1–1·6
Five main producer countries (in decreasing order)	Côte d'Ivoire, Indonesia, Ghana, Nigeria, Brazil	Brazil, Viet Nam, Colombia, Indonesia, Peru	Indonesia, Vietnam, Cote d'Ivoire, Uganda, Brazil

Fig. 1. Shade options: (a) Shaded cacao agroforestry (with natural shade trees); (b) unshaded (and herbicide-treated) cacao plantation; (c) tent technique to artificially shade cacao plant saplings when all shade trees are gone; (d) a pruned legume shade tree (*Erythrina poeppigiana*) in coffee agroforestry. Photos (a–c) from Indonesia (Central Sulawesi; a + b: T.T., c: N. Binternagel) and (d) from Costa Rica (near Turrialba; T.T.).

2002; Perfecto *et al*. 2005, 2007; Franzen & Borgerhoff-Mulder 2007; Clough, Faust & Tscharntke 2009b; Juhrbandt *et al*. 2010; see Fig. 1a,b).

In this article, we review the role of shade trees in tropical agroforestry in balancing human and ecological needs, discuss the potential ecological and economic benefits of adequate management and provide recommendations for sustainable plantation management. We place greater emphasis on cacao than coffee because shade trees in cacao systems (i) have received less attention and (ii) tend to be more endangered by recent farming practices (Table 1). Most published work provides three lines of evidence in support of shaded agroforestry: its vital role in cacao growth (Wood & Lass 2001), in biodiversity conservation (e.g. Perfecto *et al*. 2007) and in diversifying farming systems by producing timber, fruits and non-timber forest products (NTFPs) or other commodities (e.g. Rice 2008). Although some areas in Africa (e.g. Cameroon, Ghana) and Latin America (e.g. Bahia state in Brazil; Mexico) still grow cacao traditionally under permanent shade (e.g. Sonwa *et al*. 2007; Cassano *et al*. 2009), shade reduction is an ongoing process in many parts of the tropics, particularly in Southeast Asia.

We describe two types of boom-and-bust cycles in cacao systems: regional and short-term cacao boom-and-bust cycles based on changing shade regimes with age of the local plantation (within 25–30 years) and large-scale and long-term cacao cycles caused by steeply decreasing production due to unmanageable pest and pathogen problems. We review the literature on the benefits of shade trees in cacao plantations and the role of the landscape context. We conclude with suggestions that allow smallholders to sustainably use their plots over many cacao cycles, which is a major issue for agriculture and conservation management alike.

Boom-and-bust cycles in cacao production

SHORT-TERM BOOM-AND-BUST CYCLES

In their natural habitat, cacao trees grow in the understorey of closed-canopy tropical forests, commonly on nutrient-rich alluvial soils (Wood & Lass 2001). In agroforests, this shade is usually provided by thinned native forest canopy, with cacao seedlings planted in the cleared understorey, or through planted shade trees (Fig. 1a). When cacao trees mature, removal of shade trees increases (short-term) yield (Johns 1999; Steffan-Dewenter *et al.* 2007; Fig. 1b). However, when cacao trees age beyond 25–30 years in these sun (i.e. unshaded) plantations, dwindling yields and increasing pressure from insect pests lead farmers to abandon existing plantations (Johns 1999; Schroth *et al.* 2000). New forest habitats are used for new plantations that provide shade, fertile soils and low weed pressure (Ruf & Schroth 2004; Clough, Faust & Tscharntke 2009b). Shade, often called nurse shade, is essential for growing cacao seedlings and saplings (Wood & Lass 2001; Fig. 1c). Regional, short-term boom-and-bust cycles, spanning a generation of farmers, have been common in global cacao production throughout history. The ephemeral nature of shade in cacao agroforestry starting with shaded young cacao plants and gradual development into mostly or completely unshaded monocultures (Fig. 2) is a great environmental drawback. This change of shade needs with crop age differs from the situation in coffee, although general shade levels have also decreased a lot in coffee over the past decades (Perfecto *et al.* 2007).

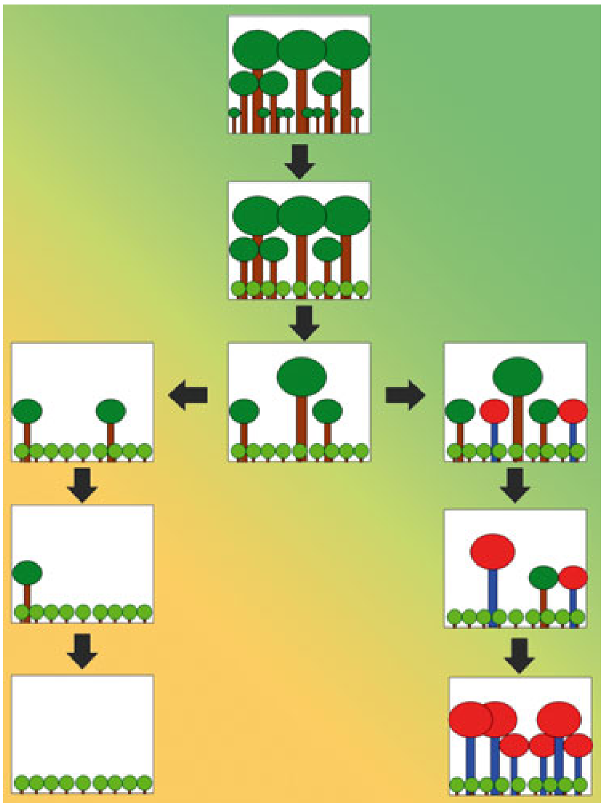

Fig. 2. A schematic diagram showing the loss of tree cover from cacao agroforestry systems. After thinning of natural forest, young cacao (light green) is planted. Natural trees (dark green and brown) are further removed and may give rise to a mono-crop plantation (on the left). The alternative (to the right) is to plant useful shade trees such as fruit trees (red and blue). In the background, the colour flow from green to yellow indicates desirable to undesirable pathways.

Rather than ringing or felling shade trees, retaining high shade levels in young cacao plantations with a stepwise increase in pruning when cacao trees grow older is a realistic and sustainable management strategy (Fig. 1d). This practice retains tree diversity and is already applied professionally by companies in Bahia, Brazil (G. Schroth, pers. obs.). Pruned shade trees of the legume genera *Gliricidia* and *Erythrina* as well as several natural forest trees allow quick re-growth when needed.

LONG-TERM BOOM-AND-BUST CYCLES

Taking a long-term and large-scale perspective, a country-wide cacao boom may be followed by cacao bust due to unmanageable pest and pathogen levels. This happened in Brazil (pathogens) and Malaysia (cacao pod borer *Conopomorpha crammerella*), leading to abandonment of cacao cultivation (Fig. 3). Unshaded cacao can rapidly degrade in the absence of anti-mirid insecticides seen, for example, on the African islands of Fernando Pó and São Tomé as well as in Ghana (Schroth *et al.* 2000). Hence, shade is often viewed by farmers as an effective insurance against insect pests, which explains why earlier government initiatives in Bahia, Brazil, had little success when trying to convince farmers to cut their shade trees and to rely on a 'technological package' of agrochemicals (Johns 1999; Cassano *et al.* 2009). Here, farmers preferred a risk-averse long-term strategy over a short-term yield gain.

Shaded cacao agroforestry suffers less from insect pest problems (Rice & Greenberg 2000), for example, suckers such as thrips and mirid bugs (Schroth *et al.* 2000), and leaf herbivory (Clough, Faust & Tscharntke 2009b; Clough *et al.* 2010), although pathogens such as the black pod disease *Phytophtora* sp. may profit from the higher humidity under planted shade trees (Schroth *et al.* 2000). However, at similar levels of shade, black pod disease has been found to be significantly reduced under a diverse layer of natural shade trees compared to just one species of planted shade trees, possibly

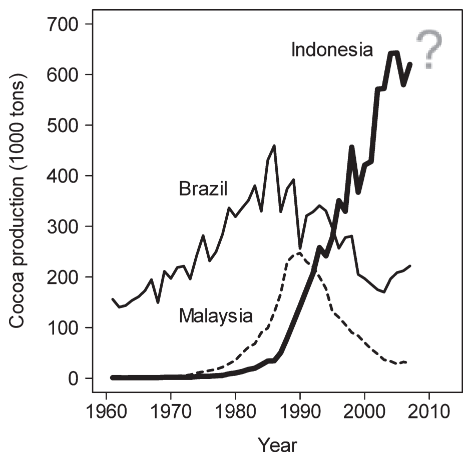

Fig. 3. Exponential growth and stagnation of cocoa production in Indonesia against the boom and bust cycles in Brazil and Malaysia: will Indonesia witness the next cacao bust? Data from FAOSTAT (2009), partly adapted from Clough, Faust & Tscharntke (2009b).

because of higher abundance and diversity of microbial antagonists (Bos, Steffan-Dewenter & Tscharntke 2007). In addition, the diversity of leaf endophytes, which are major antagonists to cacao pathogens limiting pathogen damage, is enhanced under shade (Arnold & Herre 2003). Entomopathogenic fungi can be also more efficient under shade (Schroth *et al*. 2000). Reliance on insecticides and fungicides are important cost factors reducing the advantage of potentially higher yields. The cost of pesticide use in Central Sulawesi (Indonesia) accounts for a third of total variable costs (e.g. fertilizers, pesticides and labour) of cacao plot management (Juhrbandt 2010). However, some areas depend on fungicide applications: in southern Cameroon, humidity is high and *Phytophthora megakarya* causes major losses; in Latin American, moniliasis *Moniliophthora* sp., causal agent of the witches broom disease, is prevalent. Reducing humidity by optimal pruning and spacing of shade trees is recommended (Schroth *et al*. 2000).

Two hypotheses may explain long-term pest problems in cacao production. First, pest diversity should increase with cacao area planted, as suggested by species-area relationship analyses (Strong 1974). In addition, density-area relationships suggest a positive response by herbivores to resource concentration (Connor, Courtney & Yoder 2000; Steffan-Dewenter & Tscharntke 2000), so that increasing cacao area will increase pest densities. Furthermore, connectivity between cacao trees is enhanced in densely planted crops facilitating dispersal of herbivores. Secondly, shade reduction increases physiological stress of cacao as an understorey tree (Wood & Lass 2001), making cacao more susceptible to diseases, and reduces the 'safety net' for nutrients and water provided by tree roots (see below), which also increases susceptibility to pests and diseases (Schroth *et al*. 2000; Bos, Steffan-Dewenter & Tscharntke 2007). Another disadvantage of shade loss is the increased growth of competitive weeds, especially when cacao is young (Siebert 2002), which can also act as reservoirs of pests and diseases (Schroth *et al*. 2000).

In conclusion, risk-averse farmers choose agroforestry systems that avoid long-term vulnerability by keeping shade as an insurance against insect pest outbreaks and other threats, instead of a yield-maximizing strategy aiming at short-term monetary benefits.

Benefits of shade trees within cacao plantations

SHADE TREES AS FOOD AND NON-FOOD RESOURCE

Shade trees provide biomass for construction timber or firewood, in addition to providing food resources such as fruits (Sonwa *et al*. 2007; Rice 2008). In well-managed cacao agroforests, much of the annually produced shade tree wood is pruned and used as firewood, reducing the pressure on rainforest wood (e.g. Herzog 1994; Rice 2008). Income from shade trees and other intercrops in cacao agroforestry systems in Central Sulawesi (Indonesia) accounts on average for 7% of total cacao plot revenue, but may reach up to 60% for mixed agroforestry plots (Juhrbandt 2010). Annual wood production in Indonesian cacao agroforests amounts to 3·0 tons per hectare (Moser *et al*. 2010), while 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} $year^{-1}$ (Beer *et al*. 1998). In Peru, coffee-growing smallholders derive 28% of their income from shade trees and 72% from the coffee itself (Rice 2008).

Occasionally, whole trees are removed for construction (Rice 2008). Trees can be also viewed as 'stored capital' providing a pulse of cash if families are in need. This 'tree bank' may greatly reduce vulnerability to environmental, economic or social shocks, e.g. dramatically falling prices as was the case in cocoa in the late 1980s/early 1990s and in coffee in the late 1990s/early 2000s. The same is true for fruit trees (e.g. avocado *Persea americana* and mango *Mangifera indica*), which provide shade, fruits and income security. Planting a diversity of fruit trees, shrubs (e.g. chili *Capsicum* sp., coffee) and vegetables in cacao agroforestry may greatly enhance the complexity of these systems such that they resemble diversified homegardens (e.g. Kehlenbeck, Arifin & Maass 2007; Sonwa *et al*. 2007) and promote self-sufficiency through a diversified food-and-cash-crop livelihood strategy.

SHADE TREES AS NUTRIENT 'SAFETY NET' AND 'FERTILIZER PROVIDER'

Shade trees in cacao agroforestry systems have roots that can reach beyond 2 m depth (e.g. Schwendenmann *et al*. 2010; Moser *et al*. 2010), whereas cacao trees show a more superficial root system (Lehmann 2003; Moser *et al*. 2010). In a literature review, Lehmann (2003) reports that shaded crop tree species such as coffee and cacao tend to have shallower root activity in the soil compared with fruit shade trees (e.g. citrus, guava, mango) that have particularly deep subsoil root activity. Thus, shaded cacao agroforestry systems have the 'safety net' potential to retrieve nutrients that are moving down the soil profile outside the effective root zone of cacao (Buresh *et al*. 2004).

In addition, legume shade trees such as *Gliricidia* sp. or *Erythrina* sp. greatly increase nitrogen input. Planting legume trees can be a trade-off between a natural diversification and a nutrient input-independent management. In Indonesia, deep roots in cacao agroforestry systems have been estimated to capture at least 30 kg K ha^{-1} $year^{-1}$ and at least 70 kg N ha^{-1} $year^{-1}$ (Dechert, Veldkamp & Anas 2004; Dechert, Veldkamp & Brumme 2005). The replacement costs of this natural N input by manual fertilizers include buying and applying *c*. 150 kg urea per ha. Deficiency of soil nitrogen may cause cacao fruit abortion, so agroforestry with planted legume trees could be a low-input, environmentally friendly management strategy to improve cocoa yield (Bos, Steffan-Dewenter & Tscharntke 2007).

In Ghana, cacao tree nutrient uptake and cacao biomass increased under shade tree canopy compared to a monoculture (by 43–80%, 22–45% and 96–140% for N, P, K, respectively; Isaac, Timmer & Quashie-Sam 2007a). However, adequate management of shade trees is required for optimum cacao productivity. When fertilizers are unavailable, intercropping of appropriately selected shade trees will improve light regulation and nutrient status of cacao saplings without competing too strongly (Isaac *et al.* 2007b). Root competition for soil nutrients between cacao and shade trees can be managed by timing aboveground pruning so that root growth flushes are encouraged at different times (Schroth & Zech 1995).

SHADE TREES STIMULATE LITTER DECOMPOSITION, NUTRIENT CYCLING, AND PROVIDE EROSION CONTROL

Shade trees protect the soil from adverse insolation, help maintain soil organic matter, reduce evaporation from soil, and retain soil productivity (Siebert 2002). Higher soil moisture benefits soil biota and decomposition. The mixture of leaf litter from different species (such as crop and shade trees) affects the decomposer community structure, and the litter decay and associated nutrient fluxes to the soil (Blair, Parmelee & Beare 1990). In Indonesia, annual litter production of legume *Gliricidia* trees amounts to 3·9 tons per hectare and year (Moser *et al.* 2010). Increased litter from shade trees promotes a diversity of decomposer organisms and other species that can provide ecosystem services such as pest control (e.g. Clough *et al.* 2010). Decomposers also form a critical link in ecosystem nitrogen and phosphorus cycles. A study of gross soil N transformations and availability in Indonesian cacao agroforests reports higher rates of N mineralization, ammonium uptake, and faster turnover of the ammonium pool than in an adjacent maize *Zea mays* monoculture indicating a higher N availability in agroforestry (Corre, Dechert & Veldkamp 2006). This suggests that, in contrast to maize monoculture, the decomposer community in cacao agroforests retains most of its nutrient cycling functions.

In general, soil erosion is negligible in mature cacao agroforests and losses of nutrients are insignificant unless plots are located on very steep slopes (Hartemink 2005). Shade trees play an important role in erosion control because they protect the soil against raindrop impact, reduce runoff velocity by increasing surface roughness and water infiltration as well as providing a litter layer and tree roots that create channels in the soil (Ranieri *et al.* 2004).

SHADE TREES INCREASE CARBON STORAGE AND REDUCE GREENHOUSE GAS EMISSIONS

Plant biomass and associated carbon storage are higher in shaded than unshaded cacao (Bisseleua, Missoup & Vidal 2009). In Indonesia, standing above-ground plant biomass was significantly lower in agroforestry with reduced canopy cover, mainly due to the removal of large trees (Steffan-Dewenter *et al.* 2007). This reduction corresponds to a loss in above-ground carbon storage of roughly 100 t C ha^{-1} via conversion of mainly undisturbed natural forest into low-shade agroforestry systems (Steffan-Dewenter *et al.* 2007).

Because of their high productivity, agroforests also have considerable potential to sequester carbon in soils. In a chronosequence study in Indonesia, maize monocultures lost considerable amounts of soil organic carbon with time. Conversion of maize monocultures into cacao agroforests increases soil organic carbon stocks (Dechert, Veldkamp & Anas 2004). Secondary forests on formerly degraded lands can have high soil organic carbon stocks (e.g. De Koning, Veldkamp & López-Ulloa 2003), indicating a significant soil carbon sequestration capacity of cacao agroforests. Indeed, soil carbon stocks in shaded cacao agroforests in Indonesia have been shown to differ only slightly from those of natural forests (Hertel, Harteveld & Leuschner 2009). Remarkably, the annual leaf litter C input to the soil is much lower in shaded agroforests than in natural forest, while the importance of root litter C flux to the soil is particularly high in shaded cacao agroforests. This is due to a fine-root production and turnover in cacao agroforests of a similar magnitude to natural forests (Hertel, Harteveld & Leuschner 2009).

If carbon credits are specifically targeted towards more sustainable agroforestry systems, increased environmental benefits in terms of higher carbon sequestration rates as well as higher income benefits for the poorer households can be obtained from shaded (compared to non-shaded) cacao agroforests (Seeberg-Elverfeldt 2008). A 'payment-for-ecosystem-services' scheme may build upon community conservation agreements to reduce transaction costs and integrate the local communities (Seeberg-Elverfeldt 2008).

Chemical nitrogen fertilizer applied in cacao agroforests temporarily leads to high mineral N concentrations in the soil that may become available to nitrifying and denitrifying bacteria. In Indonesian cacao agroforests, this leads to very high emissions of nitrous oxide (N_2O), an important and potent non-CO_2 greenhouse gas (Veldkamp *et al.* 2008). In contrast, cacao agroforestry systems that rely on leguminous shade trees for their nitrogen supply emit N_2O at moderate rates only, although the level of N_2O emissions is still higher than in the original forest, probably because of the faster N cycling in agroforests (Corre, Dechert & Veldkamp 2006).

SHADE TREES MITIGATE CLIMATE CHANGE EFFECTS

Large-scale removal of rainforests is likely to cause a warmer and drier climate, leading to reduced cloud formation and upward shifts of cloud condensation layers (Lawton *et al.* 2001). Changing patterns of temperature and precipitation threaten agriculture in tropical countries. In Indonesia, it has been shown experimentally that droughts affect cacao yield (Schwendenmann *et al.* 2010). Farmers in Sulawesi reported a decline of up to 38% of average cacao yield levels after strong ENSO (El Niño Southern Oscillation) related droughts in 1997 and 2002, which forced farmers to reduce expenditures for food and other basic necessities (Keil *et al.* 2008). As farmers were ill prepared, they adopted environmentally damaging and illegal activities such as rattan *Calamus* sp. extraction from protected forests (Keil *et al.* 2008). ENSO years can also decrease coffee production by 40–80%; shade trees, however, can mitigate temperatures and precipitation extremes as well as wind and storm events, thereby limiting potential income losses (Philpott *et al.* 2007; Lin, Perfecto & Vandermeer 2008).

Severe drought also increases the risk of fires on cacao farms (Johns 1999).

In Sulawesi, shade trees and shade tree planting are used to protect cacao systems against droughts and increase resilience (Binternagel *et al.* 2010). Air and soil temperatures are lower and air humidity levels higher under shade, which often reduces water stress for cacao (Lin, Perfecto & Vandermeer 2008). Shade trees reduce evaporative demand and, hence, drought stress of cacao plants. In a cacao/*Gliricidia* agroforest in Sulawesi, increased canopy cover from shade trees has been shown to enhance water uptake and increase cacao stem diameter and leaf area (Köhler *et al.* 2009). Enhanced vegetative growth under shade trees has also been observed in cacao stands in Ghana (Isaac *et al.* 2007b).

Improved growing conditions and reduced drought stress in shaded conditions are also seen in coffee (Perfecto *et al.* 2007). Transpiration rates of coffee grown in full sun were higher than coffee under shade trees, when expressed as per unit leaf area but not when expressed in per unit ground area. The increased transpiration per unit ground surface of coffee under shade trees was attributed to increased vegetative growth (Perfecto *et al.* 2007).

Shade trees in cacao enhance rainfall interception and thereby reduce water input to the soil (Dietz *et al.* 2006). Shade trees in agroforests are often assumed to affect negatively growth and yield of cacao plants through competitive water use, but empirical studies have shown positive effects of plant species-specific, complementary resource use in agroforestry systems (Ong, Kho & Radersma 2004). An understanding of the different root attributes of intercropped tree, such as contrasting spatial rooting pattern, root morphology, and mycorrhizal status, is important to achieving such complementary resource use (Ewel & Mazzarino 2008).

Data on vertical water uptake depth based on stable isotope analyses suggest complementarity between cacao trees and shade trees. There is pronounced vertical root segregation (Moser *et al.* 2010) with cacao trees mainly using water from the upper soil layer, whereas *Gliricidia* shade trees mainly use water from deeper soil layers (Schwendenmann *et al.* 2010). Complementary water resource use by deep rooting and redistribution of soil water to cacao roots in the upper soil layers translates to sustainable resource use and higher yields in shaded cacao agroforestry (Ewel & Mazzarino 2008).

Overall, shade trees play a mixed role in cacao agroforestry. On the one hand, shade trees may enhance drought susceptibility by increasing stand transpiration, through both their own water use and by increasing water use rates of cacao trees with higher vegetative growth. On the other hand, susceptibility can be reduced because of complementary water resource use by cacao and shade trees and the redistribution of soil water by shade trees to cacao. The outcome will depend on environmental factors such as drought severity and shade tree composition.

SHADE TREES ENHANCE FUNCTIONAL BIODIVERSITY

Shaded cacao and coffee systems are known to support much higher biodiversity than unshaded systems (Schulze *et al.* 2004; Shahabuddin *et al.* 2005; Perfecto *et al.* 2007; Sonwa *et al.* 2007; Steffan-Dewenter *et al.* 2007; Cassano *et al.* 2009; Clough *et al.* 2010). Examples from around the world suggest that tropical agroforestry systems can harbour high levels of biodiversity, often comparable to native forest, even though species composition often differs greatly (see Table S2, Supporting Information). Higher biodiversity in shaded agroforests can be related to an increase in functionally important groups (Tscharntke *et al.* 2008). These include insectivorous birds and bats (Cassano *et al.* 2009; Clough *et al.* 2009a), tree seed-dispersing birds (Lozada *et al.* 2007), pollinators enhancing crop yield (Olschewski *et al.* 2006; Priess *et al.* 2007), parasitoids increasing parasitism rates (Sperber *et al.* 2004; Tylianakis, Tscharntke & Klein 2006) and amphibians providing biocontrol services (e.g. control of the invasive ant *Anoplolepis gracilipes* in Indonesia by endemic toads, Wanger *et al.* 2010a). Cacao pollination by midges is little known, but it is a key determinant of cacao yield that may benefit from shade (Groeneveld *et al.* 2010). Functional biodiversity in agroforestry systems benefits from tall shade trees and shade tree diversity (van Bael *et al.* 2008; Clough *et al.* 2009a, 2010) and will increase their overall resistance and resilience (Fig. 4).

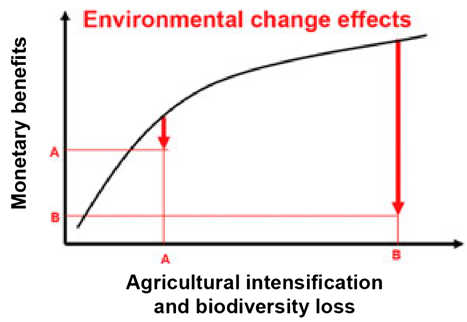

Fig. 4. Conceptual model illustrating increasing vulnerability to environmental (and economic and social) change with agricultural intensification. Shade tree loss can be used as a proxy for agricultural intensification in agroforestry. Monetary benefits (households' income stability) decrease less in low intensity (A) than high intensity production systems (B).

Shade trees in a landscape context

Biodiversity must be viewed at the landscape scale, because most species respond to their environment on this level, including spillover across managed systems and natural habitat (Hedlund *et al.* 2004; Tscharntke *et al.* 2005, 2008; Vandermeer & Perfecto 2007). Local alpha diversity, instead of (landscape-wide) beta diversity, can underestimate the value of land-use types such as agroforestry (Tylianakis, Klein & Tscharntke 2005; Kessler *et al.* 2009). The proximity of natural forest is a key predictor for species richness of plants, invertebrates and vertebrates in agroforestry, while endemics and forest specialists benefit most from indigenous shade tree cover (Clough *et al.* 2010). Insectivorous and seed-dispersing birds (Clough *et al.* 2009a), biocontrol services by toads as well as amphibians and reptiles (Wanger *et al.* 2010a,b), parasitic wasp diversity (Cassano *et al.* 2009), the diversity of bees, wasps and parasitoids (Klein, Steffan-Dewenter & Tscharntke 2006), and endemic rats *Rattus* sp. are all known to benefit from proximity to forest edge (Cassano *et al.* 2009; Clough *et al.* 2010). In addition, shaded cacao agroforestry can be important buffer zones around rainforest reserves, reducing forest edge effects and increasing connectivity among forested habitats.

Practical recommendations for shade-tree management

Shade removal to attain short-term increases in cocoa yield (Johns 1999; Steffan-Dewenter *et al.* 2007; Clough, Faust & Tscharntke 2009b) will have negative long-term effects that jeopardize the sustainability of cocoa production (Figs 3 and 4). Within cacao and coffee agroforestry, the amount of crop shading cover is a proxy of agricultural intensification (Beer *et al.* 1998). The environmental value of shade trees is provided by their forest-like structure (Perfecto *et al.* 2007). They also have social and economic value in reducing the vulnerability of households to climatic stress, pest outbreaks, falling prices and food insecurity. Short-term yield gains through shade removal may reduce the long-term resistance and resilience of the system, due to unmanageable pest pressure, vulnerability to changing climate and difficulties to rejuvenate cacao. Reaping the long-term advantages of shaded cacao agroforestry does not exclude intermediate levels of agroforestry intensification: reducing canopy cover from 80% to 40% can double the income of local farmers with only minor changes in biodiversity and associated ecosystem services (Steffan-Dewenter *et al.* 2007).

At a practical level, it is important to enrich natural shade-tree diversity by planting legume trees, which should be pruned gradually as the cacao trees age. When rejuvenation of cacao is needed after 25–30 years, farmer should stop pruning the trees, allowing the shade to increase to levels appropriate for seedling establishment, reinitiating the cacao cycle in the same plot and thereby avoiding the need to thin new areas of forest to establish new cacao plantations. Although appropriate management and pruning methods for planted legume trees are well known for many species, little is known about the management of native forest trees; therefore, more detailed information on pruning sensitivity is urgently needed for these species. Shade quality, i.e. crown size, crown density and compactness of the crown, requires well-informed management decisions. However, despite the long history of cacao cultivation, with companion trees throughout the world, the shade strata of cacao plantations are often sub-optimally designed and managed (E. Somarriba, statement at the 15th International Cocoa Research Conference; 9–14 October 2006, Costa Rica).

Payment-for-ecosystem-service schemes and crop certification (such as Rainforest Alliance©; UTZ certified or Bird friendly; Philpott *et al.* 2007), in which a premium is paid for cocoa cultivated under a diverse layer of shade trees, would help increase economic benefits while simultaneously providing incentives to farmers to maintain shade (Franzen & Borgerhoff-Mulder 2007). The certification schemes established for shade-grown coffee in Mesoamerica suggest that these mechanisms can potentially help stabilize shade-cacao agroforestry (Perfecto *et al.* 2005). However, biodiversity conservation measures aiming at more sustainable ways of cacao cultivation will be unlikely to be successful without creating economic incentives for cocoa farmers. Compared with the annual revenues from more intensive cacao plantations of several hundred US$ per year, the disutility from shading *per se* appears to be rather low (<4 US$ ha^{-1} year^{-1} per 40–50% shade increase). Thus, the introduction of a certification scheme for high-shading 'biodiversity-friendly' cocoa production may realistically achieve a price premium per hectare that suffices to offset high-shade disadvantages (Steffan-Dewenter *et al.* 2007).

Investment is needed to encourage and educate local farmers about the diverse ecosystem services provided by

Table 2. Six rules for shade management in tropical agroforestry reducing economic vulnerability of cacao agroforestry systems needs sustainable shade management (see Fig. 4)

(1) Conserve or create a diverse layer of shade trees, combining natural shade trees (for enhanced functional biodiversity, erosion control, carbon sequestration, soil fertility, drought resistance, etc.) with particularly useful multi-purpose species such as legume trees (for nitrogen fixation, wood production) (Bhagwat *et al.* 2008)

(2) Prune, but do not remove shade trees, allowing high shade levels (nurse shade) for cacao seedlings and saplings, shade reduction during the main cultivation period and again, high shade when rejuvenating aged, low-yield plantations. Such shade management avoids regional short-term and large-scale, long-term cacao boom-and-bust cycles (Clough, Faust & Tscharntke 2009b)

(3) Reduce spraying of herbicides, fungicides and insecticides to protect functional biodiversity (e.g. pollination and biological control), which will become even more important under environmental change, and employ integrated pest management (Franzen & Borgerhoff-Mulder 2007; Veddeler *et al.* 2008; Groeneveld *et al.* 2010)

(4) Keep natural forest in the vicinity of agroforests to allow forest species to spillover into agroecosystems and to use resources in cacao and coffee agroforestry, thereby increasing functional biodiversity in agroforests (Tscharntke *et al.* 2008)

(5) Implement incentives encouraging farmers to keep high to medium shade cover. Payment-for-ecosystem-service (PES) and carbon financing have been suggested as well as biodiversity-friendly crop certification or organic production systems (Philpott *et al.* 2007)

(6) Optimize the management of the shade strata, combining high biodiversity and sustainable crop production with high yield. Promote self-sufficiency through a 'diversified food-and-cash-crop' livelihood strategy (Steffan-Dewenter *et al.* 2007). This approach is likely to be most effective if it involves a transfer of farmers' traditional knowledge across cacao producing regions as well as from farmers to agronomists and scientists and *vice versa*

shaded systems. The willingness to improve shade-tree management and implement certification schemes is likely to be most effective if it involves a transfer from farmers' knowledge to scientists and vice versa (Table 2). In the face of climate changes and price fluctuations on a global scale, introducing adequate incentives may determine whether permanently shaded cacao agroforestry can survive as a source of biodiversity and economic security alike (Fig. 4).

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Table S1. Comparing features of cacao and coffee agroforestry.

Table S2. Species richness and community similarity reported from cacao agroforestry systems (see below for cited references).

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