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RESEARCH ARTICLE

Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes

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Abstract

Purpose Conversion of shaded agroforests to unshaded monocultures endangers the resilience of tropical landscapes. Landscape-scale impacts of alternative shade managements have rarely been assessed. This study explored plantation- and landscape-level impacts of different shade management strategies on aboveground biomass, functional group diversity, and economic potential of cocoa production in northern Ecuador.

Methods We simulated several cocoa shade management scenarios, using the dynamic forest model LANDIS-II: (i) 'baseline' projections representing the current mosaic of traditional agroforests, planted agroforests, and unshaded monoculture plantations; (ii) 'traditional' agroforestry shaded by native fruit and timber trees; (iii) 'planted' agroforests shaded by planted fruit trees; and (iv) 'monoculture' unshaded plantations. The impacts of setting aside 20, 30, and 40% of cocoa plantations for natural regeneration was tested for the monoculture scenario.

Results Traditional agroforests shaded by native trees stored up to 7% more aboveground biomass and had higher abundances of rare functional groups compared to monocultures after 50 years of simulation. Smaller effects were found for planted agroforests. Shaded plantations and land set aside for natural regeneration reduced forest fragmentation at the landscape level. The estimated yield gap for monoculture and shaded plantations could not be compensated by additional revenues for carbon storage at current carbon market price.

Conclusions Improving payment-for-ecosystem services and certification schemes are needed to incentivize smallholders to maintain substantial non-cocoa tree cover that may provide an environmental-friendly way to improve economic potential and food security for smallholders, while supporting biomass and functional group diversity at the landscape level.

Keywords Aboveground biomass · Biodiversity · Cacao agroforestry · Ecuador · LANDIS-II · Payments for ecosystem services · Economic revenues

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Introduction

Forest conversion and agricultural intensification are important causes of loss of biodiversity and associated ecosystem services (Foley et al. 2005). To adapt to environmental and climate changes, resilient agricultural landscapes are needed to safeguard ecosystem services and food security. Yet, agricultural intensification reduces the response capacity of land-use systems to environmental stresses (Tscharntke et al. 2011; Balthazar et al. 2015). Shaded agroforestry systems offer an alternative to intensive monoculture systems. Many scholars have identified shaded agroforests as a biodiversity-friendly way to produce food and guarantee economic returns, while sustaining ecosystem services (e.g., Perfecto et al. 2007; Schroth and Harvey 2007; Steffan-Dewenter et al. 2007; Bhagwat et al. 2008; Tscharntke et al. 2011, 2015; Vaast and Somarriba 2014).

Cocoa is commonly grown under shade from non-cocoa trees (Rice and Greenberg 2000) and covers about 10 million ha of land globally (FAO 2014). Compared to intensive monoculture systems, shaded cocoa agroforests can support high levels of biodiversity (De Beenhouwer et al. 2013; Asase and Tetteh 2016) and play a role in the carbon cycle by storing carbon in above- and belowground biomass (Albrecht and Kandji 2003; Kessler et al. 2012; Somarriba et al. 2013; Obeng and Aguilar 2015). Trees in tropical agricultural landscapes determine key landscape characteristics and ecosystem services' delivery (Clough et al. 2009a; Tscharntke et al. 2011; Mendenhall et al. 2014).

Many farmers worldwide convert shaded agroforests to more intensively managed plantations by reducing the number of non-cocoa trees, in an attempt to increase short-term economic returns (Steffan-Dewenter et al. 2007; Clough et al. 2009b; Vaast and Somarriba 2014). Cocoa cultivation has been estimated to cause 14–15 million ha of tropical deforestation globally (Clough et al. 2011). Decreasing tree cover in tropical agricultural landscapes might affect landscape functioning far beyond the farm level. Some authors argue that agricultural intensification may free up other areas for nature conservation through land sparing, which may compensate for the loss of ecosystem services from intensification (Green et al. 2005; Phalan et al. 2011a, b). By contrast, wildlife-friendly farming, also referred to as land sharing, integrates low-intensity agricultural production with natural landscape elements, resulting in a patchy landscape (Tscharntke et al. 2012; Milder et al. 2014). Some scholars have suggested that agroforestry farming methods may thus enhance the matrix quality of human-dominated agricultural landscapes (Perfecto et al. 2009, 2010; Chappell and LaValle 2011; Fischer et al. 2014). While several studies have quantified biodiversity and biomass changes along intensification gradients in shaded agroforestry systems (Steffan-Dewenter et al. 2007; Bisseleua et al. 2009; De Beenhouwer et al. 2013; Vaast and Somarriba 2014; Obeng and Aguilar 2015), the role of shade management and impacts of land sparing at the landscape level have rarely been assessed.

The objective of this study was to understand the landscape-level impacts of different cocoa shade management strategies on aboveground biomass (AGB), biodiversity, and the economic potential of cocoa plantations. We modeled seven alternative management scenarios representative of cocoa farmers in northern coastal Ecuador, using the well-established ecological model LANDIS-II. The Neotropical moist forest of the northern coast is unique for its high number of endemic plants, and one of the highest avian endemism in the world: about 2500 of the 10,000 identified plant species are endemic and 650 species of birds were identified (Dodson and Gentry 1991). The area of primary forest is rapidly declining, with small patches of remnant forest that are subject to the edge effect. Several species are critically endangered due to habitat fragmentation and hunting, such as the *Crocodylus acutus* (Groombridge and Wright 1982) and *Panthera onca* (Saavedra et al. 2017), and a large number of birds in the region are threatened or nearly extirpated, such as *Harpia harpya* (Miranda 2015). Almost half of the critical biodiversity areas are close to recent (2008–2014) areas of habitat conversion and degradation (Cuesta et al. 2017), reinforcing the need to engage in conservation strategies where biodiversity co-benefits can be optimized.

Four scenarios explored the impact of alternative shade management ranging in type and percentage of non-coca trees on cocoa plantations, and three scenarios assessed how much cocoa agroforestry land should be set aside for natural regeneration in a scenario of conversion to monoculture to reach levels of aboveground biomass at the landscape scale comparable to our baseline projections. These various scenarios represent both the land sharing and land sparing approaches to biodiversity management. Finally, to explore the impact of shade management (i.e., land sharing) and of land sparing on economic potential, we estimated landscape-level revenues from cocoa production and payments for additional carbon stored in carbon markets. We restricted the study to carbon payments given data availability. This study contributes to the literature on shaded agroforestry systems by quantifying landscape scale impacts of cocoa agroforestry systems. The results may inform the design of payment-for-ecosystem services and certification schemes to promote productive and biodiversity-friendly shade management regimes.

Methods

Study region

We conducted this study in the northern province of Esmeraldas, where we focused on the five main cocoa producing western cantons (8470 km^2; 54% of the surface area of Esmeraldas; Fig. 1). Esmeraldas is amongst the poorest provinces of Ecuador, with a high percentage of smallholders owning on average 5 ha of land. The main commodities produced in this region are cocoa beans, fresh fruits (e.g., bananas, oranges, maracuyas) and, increasingly, palm oil. An agricultural survey conducted by the Ecuadorian Ministry of Agriculture in 2013 estimated that about 52,884 ha in Esmeraldas was planted with cocoa, producing a total of 13,343 metric tons of dry cocoa beans (i.e., average yield of 252 kg per ha) (ESPAC 2014).

Chocolatiers have shown particular interest in this region for the high-quality fine flavor cocoa beans, known as ‘Nacional’, traditionally grown in shaded agroforestry systems. Most of the traditional cocoa plantations in Ecuador have a low productivity due to low-yielding planting material, aged cocoa trees and high vulnerability to diseases, such as witches’ broom and moniliasis (Amores et al. 2011). Many smallholders have intensified production systems by reducing shade levels and replacing traditional Nacional varieties with clonal varieties, mainly CCN-51 (Hernández et al. 2014). CCN-51 trees are more disease-resistant and productive, less susceptible to sun damage, and are often planted densely without associated non-cocoa trees (Bentley et al. 2004). Production potential of CCN-51 trees was found to be between 53 and 275% higher than Nacional-type trees in controlled production experiments (Amores et al. 2011; Boza et al. 2014). Monoculture plantations may provide increased yield, but require more agrochemical inputs and are more susceptible to droughts, soil erosion and degradation (Jacobi et al. 2014). On specialized markets, high-quality Nacional beans may receive up to 60% above standard cocoa market price for their appreciated flavor—but cocoa prices do fluctuate as production varies. Nevertheless, a differentiated farm-gate price was absent for CCN-51 and Nacional beans in Esmeraldas for 2014; respectively US$1.93 and US$2.02 per kilogram (SINAGAP 2015; PRAGMATICA 2016).

We identified three cocoa plantation types in the study region based on shade level and type, following the classification proposed by Rice and Greenberg (2000): (i) cocoa with traditional shade, planted under thinned natural forest (e.g., *Aegihila alba*, *Guazuma ulmifolia*, *Schizolobium parahyba*, *Cecropia* spp.) with less than 20% planted fruit, legume, or timber trees; (ii) cocoa with more than 20% planted shade, such as leguminous trees (e.g., *Inga* spp., *Erythrina* spp.), fruit trees (e.g., *Citrus* spp. *Carica papaya, Persea Americana, Mangifera indica*) and timber trees (e.g., *Cordia alliodora, Cedrela odorata, Handroanthus* spp.); and (iii) monoculture cocoa plantations without shade.

LANDIS-II parameterization

To simulate woody species establishment, growth and mortality, we used the spatially explicit forest landscape model LANDIS-II (Scheller et al. 2007). This well-established model simulates forest dynamics over large spatial scales by incorporating ecological processes, such as succession, disturbance, and seed dispersal. LANDIS-II has been applied in Latin America to support conservation planning in Chile (Newton et al. 2011), to assess the potential for forest restoration in Mexico (Cantarello et al. 2011) and Ecuador (Middendorp et al. 2016), and to predict the spatial extent of forest restoration (Birch et al. 2010). The model can deal with multiple disturbances, such as timber harvest, forest conversion (Thompson et al. 2011), and land use (Thompson et al. 2016). LANDIS-II tracks age cohorts for each simulated species, ignoring individual trees, to achieve computational

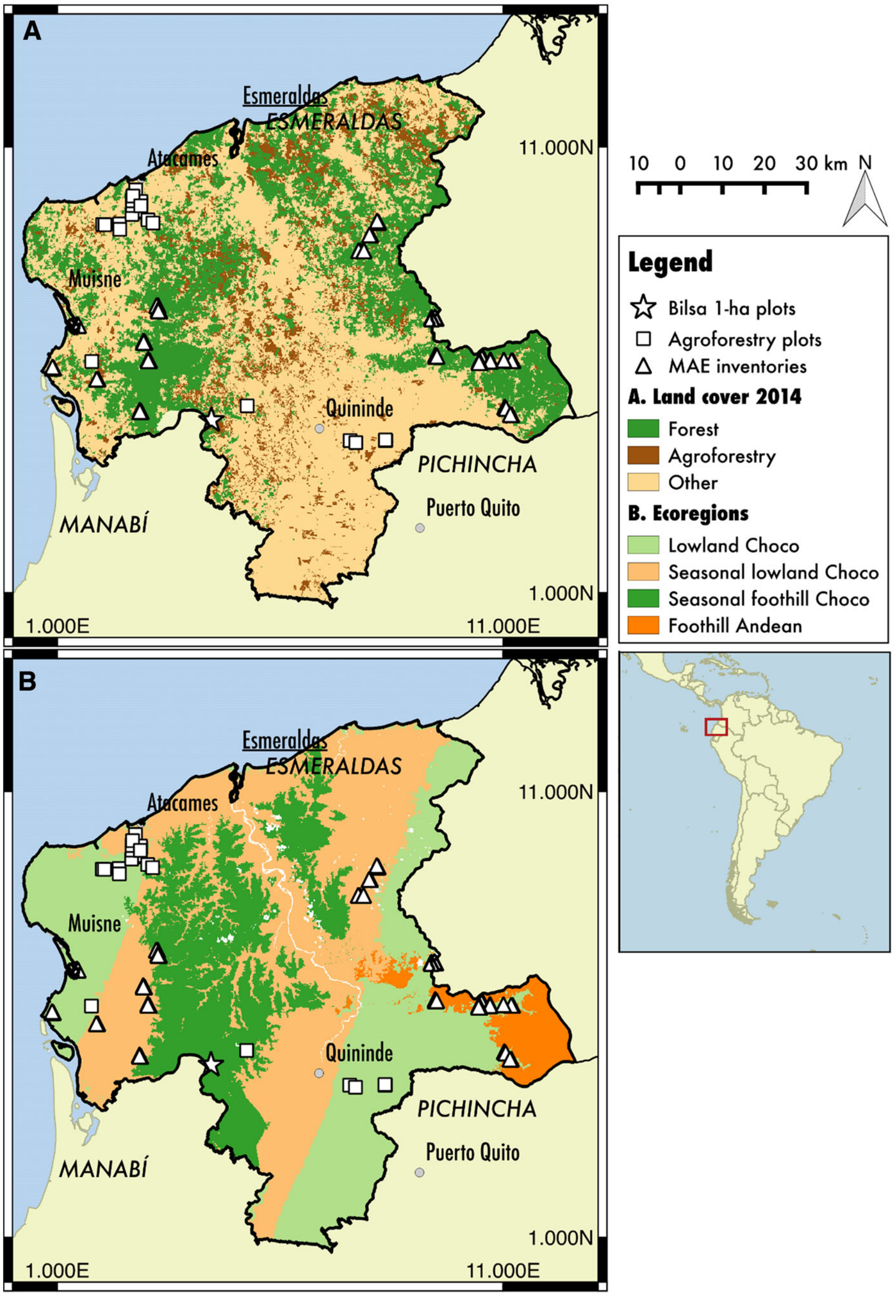

Fig. 1 Study region in northern Ecuador comprised of the five western cantons of the Esmeraldas province (Muisne, Atacames, Esmeraldas, Rio Verde and Quininde). **A** Ecoregions were considered to be homogeneous in climatic and soil conditions (see Table 2 for details). Cacao agroforestry plots (squares), forest inventory plots collected by the Ecuador Ministry of Environment (MAE) (triangles) and 1-ha multi-census forest inventories in the Bilsa Biological station (stars) are indicated. **B** 2014 Land cover classification created by MAE (2014); cover types relevant for simulations were forest (dark grey), cacao agroforests (black) and others (i.e., pasture, agriculture, urban; light grey)

tractability. We implemented the Biomass Succession extension of the LANDIS-II model (v. 3.2) tracking live aboveground biomass (AGB) estimates for species cohorts influenced by growth, senescence, and management disturbance on all active landscape cells (i.e., cells for which forest ecological processes took place, classified as forest and agroforests) for each 10-year time step.

Land cover map

The Ecuadorian Ministry of Environment (MAE) in collaboration with the Food and Agriculture Organization of the United Nations (FAO) created a land cover classification at 30 m spatial resolution, based on unsupervised classification with field validation for a LANDSAT and Aster mosaic consisting of satellite images from 2014 (Fig. 1b) (MAE 2014). The 2014 classification was validated using field observations for 500–1000 random sample points in each LANDSAT image, resulting in an average accuracy of 79% and a Kappa coefficient of 76%. LANDIS-II simulations were restricted to the five main cocoa producing western cantons and areas classified as natural forest remnants (about 31.4% or 2646 km^2) and cocoa agroforestry (about 10.5% or 887 km^2), whereas remaining areas classified as agriculture, pastures, and build-up (about 58.1% or 4937 km^2) were ignored for simplification and lack of field data. This resulted in an underestimation of total landscape AGB and functional group diversity, which is defined as the variation in sets of species that share similar characteristics and play an equivalent role in a community.

Field data

We assessed the woody plant richness and composition of cocoa plantations in 43 plots of 20 × 50 m (0.1 ha) (Fig. 1a). Each individual taller than 2 m was identified to species level and the diameter at breast height (dbh) and height were recorded. To determine the woody plant richness and composition of natural remnant forests, we obtained forest inventory data collected by the Ecuadorian Ministry of Environment (MAE) in 172 patches of natural forests of 60 × 60 m (0.12 ha) located throughout our study region. The dbh, height, and genera of each live woody individual taller than 20 cm dbh were available for each plot. For both datasets, AGB estimates for all collected individuals were calculated with the Chave et al. (2005) allometric equation for moist forests, using the dbh and height measurements, as well as species-specific estimates of wood density for South-America from the Global Wood Density Database (Chave et al. 2009; Zanne et al. 2009).

To initialize dynamic aboveground net primary productivity (ANPP) rates of functional groups, we used growth data from three 1-ha multi-census forest inventory plots at the Bilsa Biological Station located in the southernmost part of Esmeraldas (00°21′N 79°44′W) (Clark et al. 2006). The same estimates were used for all varieties of cocoa tree. We derived ANPP estimates for each individual based on diameter increments for surviving trees only. Total ANPP estimates for these plots ranged from 772 to 1391 g biomass m^{-2} year^{-1}, which fall in the range of other reported values [280–3010 g m^{-2} year^{-1} (Clark et al. 2001); 2120 g m^{-2} year^{-1} (Chave et al. 2010); 2470 g m^{-2} year^{-1} (Keeling and Phillips 2007)]. ANPP estimates for cocoa trees were extracted from a study of 229 permanent sample plots in cocoa agroforestry systems in five Central American countries (Somarriba et al. 2013) (i.e., 360 g AGB m^{-2} year^{-1}). Currently, data on ANPP are limited for tropical forests, thus the presented ANPP values must be viewed as rough estimates.

Initial composition and distribution of functional groups

We selected the 20 most dominant genera from the MAE forest inventories and clustered these into six functional groups based on wood density estimates from the Global Wood Density Database (Chave et al. 2009; Zanne et al. 2009) (Table 1). In tropical trees, wood density is a key functional trait positively correlated with competition ability, survival rate and shade tolerance, and negatively associated with growth rate (Poorter et al. 2010a, b, Kunstler et al. 2016). Abundant palm genera were omitted (i.e., *Wettinia* and *Iriatea*), as growing characteristics of monocots are not well represented in LANDIS-II. The initial distribution of functional groups across the landscape was mapped by combining the land cover map with the field data. MAE forest inventories were randomly distributed over cells classified as forests, whereas cocoa plantation plots were categorized following the three plantation types described in Study region section and then randomly distributed over cells classified as agroforestry.

Age estimates for each individual were made by dividing the maximum measured dbh from the MAE forest inventories with the maximum ANPP estimated from the Bilsa forest inventory plots for each functional group (Lieberman et al. 1985). Any error in the estimation of initial tree ages affects the initial distribution only, because LANDIS-II is independent of age-growth relationships. Longevity for each genus was determined based on the maximum observed dbh found in the MAE inventories and the maximum ANPP for that genera found in the Bilsa plots. Estimates were checked for consistency against maximum reported values from the literature (Table 1).

Table 1 Functional group (i.e., Fg) characteristics

Name	Long[a]	Mat	ShTol	Disp		MaxANPP[b]	MaxB[b]	WD[c]	Forest genera	Agroforest genera	Description
				Effective	Max						
Fg 1	120	22	2	50	400	258	52.6	0.28	*Apeiba, Cecropia*	*Cecropia, Erythrina*	Fast-growing native pioneers
Fg 2	340	66	3	50	400	377	275.2	0.64	*Brosimum, Miconia*	*Dussia, Psidium*	Understory to canopy trees
Fg 3	480	95	4	400	1500	1083	203.8	0.79	*Castilla, Pouteria*	*Cupania, Pouteria*	High wood density timber trees
Fg 4	580	115	3	400	1500	640	178.1	0.54	*Inga, Matisia*	*Carica, Citrus, Inga*	Fruit trees (mainly planted)
Fg 5	340	67	2	50	400	792	123.5	0.39	*Otoba, Pourouma*	*Annona, Pourouma*	Fruit trees (native)
Fg 6	290	56	3	50	400	258	148.4	0.48	*Trattinnickia, Virola*	*Cedrela, Cordia*	Medium wood density timber trees
Cocoa	80	4	5	1	1	360	17.9	–	–	*Theobroma*	Shade-tolerant understory shrubs

Long longevity (years), *Mat* sexual maturity (years), *ShTol* shade tolerance, *Disp* effective and maximum seed dispersal distance (m), *WD* mean wood density (g m^{-3}), *maxANPP* maximum aboveground net primary productivity rate (g m^{-2}), *maxB* maximum biomass (Mg ha^{-1})

[a] (Lieberman et al. 1985; Korning and Balslev 1994; Laurance et al. 2004)

[b] Values represent the maximum aboveground net primary productivity (ANPP) rates and maximum biomass (maxB) for each functional group over the different ecoregions (i.e. values differ between ecoregions)

[c] Means from the Global Wood Density Database (DRYAD) for South-America (Chave et al. 2009; Zanne et al. 2009)

Species establishment probabilities

Four ecoregions were delineated by overlaying a digital elevation model with an annual average rainfall map (Table 2, Fig. 1a). Climatic and establishment conditions were assumed to be homogeneous within each ecoregion during the period of simulations. The maximum observed AGB in the MAE forest inventories was assigned for each functional group and for each ecoregion. Maximum AGB estimates for cocoa trees were extracted from Somarriba et al. (2013) (i.e., 1797 g AGB m^{-2}). Functional group establishment probabilities were derived from MaxEnt models (Phillips et al. 2006) as the average probability of occurrence for each functional group in each ecoregion. Input data for these models included species occurrence data from the MOBOT Tropicos® database (©2014 Missouri Botanical garden, USA) and bioclimatic variables extracted from the Worldclim database (Hijmans et al. 2005). Occurrence data were checked for coordinate accuracy and only field observations were used, omitting controlled experiment observations.

Model validation and sensitivity

LANDIS-II is a stochastic model and does not predict actual events. We performed a sensitivity analyses on six key parameters: maximum ANPP, maximum AGB, ANPP shape, mortality shape, establishment probability, shade tolerance, and species longevity. Continuous parameters were altered by increments of 10% and categorical parameters were altered by increments of 1 unit, after which the impact on the total AGB estimate was assessed at the onset and end of baseline simulations (Scheller and Mladenoff 2004; Thompson et al. 2011). To evaluate the parameterization of the model, we compared AGB estimates at

Table 2 Description of ecoregions used to define homogeneous areas

Ecoregion	Description	Mean altitude (masl)	Mean precipitation (mm/year)[a]	Mean PET (mm)[b]	Mean NPP (gC/m^2/year)[c]
1	Evergreen lowland Choco forest	137	2784	1442	9549
2	Evergreen seasonal lowland Choco forest	114	1736	1432	9453
3	Evergreen seasonal foothill Choco forest	293	1468	1398	5548
4	Evergreen foothill and mountain Andean forest	545	3845	1470	8372

Mean altitude and precipitation were used to delineate ecoregions, whereas mean PET and NPP were used to scale ANPP values over different ecoregions

[a] Worldclim database: BIO12 (Hijmans et al. 2005)

[b] Global potential evapo-transpiration (Trabucco and Zomer 2009)

[c] Mean net primary productivity for Terra Modis 2000–2015 maps (Running et al. 2004; Zhao et al. 2005)

simulation onset to the values observed in the MAE forest inventories, using Pearson's correlation coefficient and RMSE. All model results were averaged over five simulation runs. Increasing the number of replicates did not decrease total between-run variability (less than 2–3%), thus five replicates were deemed sufficient, as is common practice in LANDIS-II applications (e.g., Cantarello et al. 2011, 2014; Thompson et al. 2011; Duveneck et al. 2014; Mairota et al. 2014).

Simulation experiment

Agroforestry management scenarios

Agroforestry management was modeled using the Biomass Harvest extension (v. 3.0) of the LANDIS-II model. We designed seven landscape management scenarios, which ranged in the level and type of shade maintained in cocoa plantations (Fig. 2; Table 3). Four scenarios explored the impact of alternative shade management ranging in type and percentage of non-coca trees on cocoa plantations: (i) 'baseline' resembling a persistence of the current patchy landscape with a mix of traditional, planted, and monoculture plantations; (ii) 'traditional' agroforestry shaded by native fruit and timber trees; (iii) 'planted' agroforests shaded by planted fruit trees; and (iv) 'monoculture' unshaded plantations. Three additional scenarios assessed how much cocoa agroforestry land should be set aside for natural regeneration in a scenario of conversion to monoculture systems to reach levels of aboveground biomass at the landscape scale comparable to the baseline scenario. We tested percentages of land set aside of 20, 30, and 40% in the least accessible plots (i.e., greatest distance to roads) located in areas with high potential for biodiversity conservation, as identified by Cuesta et al. (2017) (respectively scenario iv-a, iv-b, and iv-c) (Fig. 2; Table 3; Fig. A1). Extensive remnant forest patches are present in these high potential areas, likely favoring natural regeneration in abandoned plantations by providing a seed source for plant dispersal. For each scenario, we analyzed changes in AGB and in functional group diversity at the plantation and landscape levels.

Economic potential estimations

To explore the impact of shade management and land sparing on economic potential, we estimated landscape-level revenues from cocoa production and payments for additional carbon stored compared to the baseline levels in carbon markets. First, we estimated the economic potential from cocoa bean production for each scenario at the plantation and landscape levels based on the mean aboveground net primary productivity (i.e., ANPP) modeled for cocoa trees. As LANDIS-II does not simulate cocoa bean production directly, dry bean yield was estimated by assuming that 76% of cocoa ANPP was partitioned to producing beans, as reported for traditional, planted,

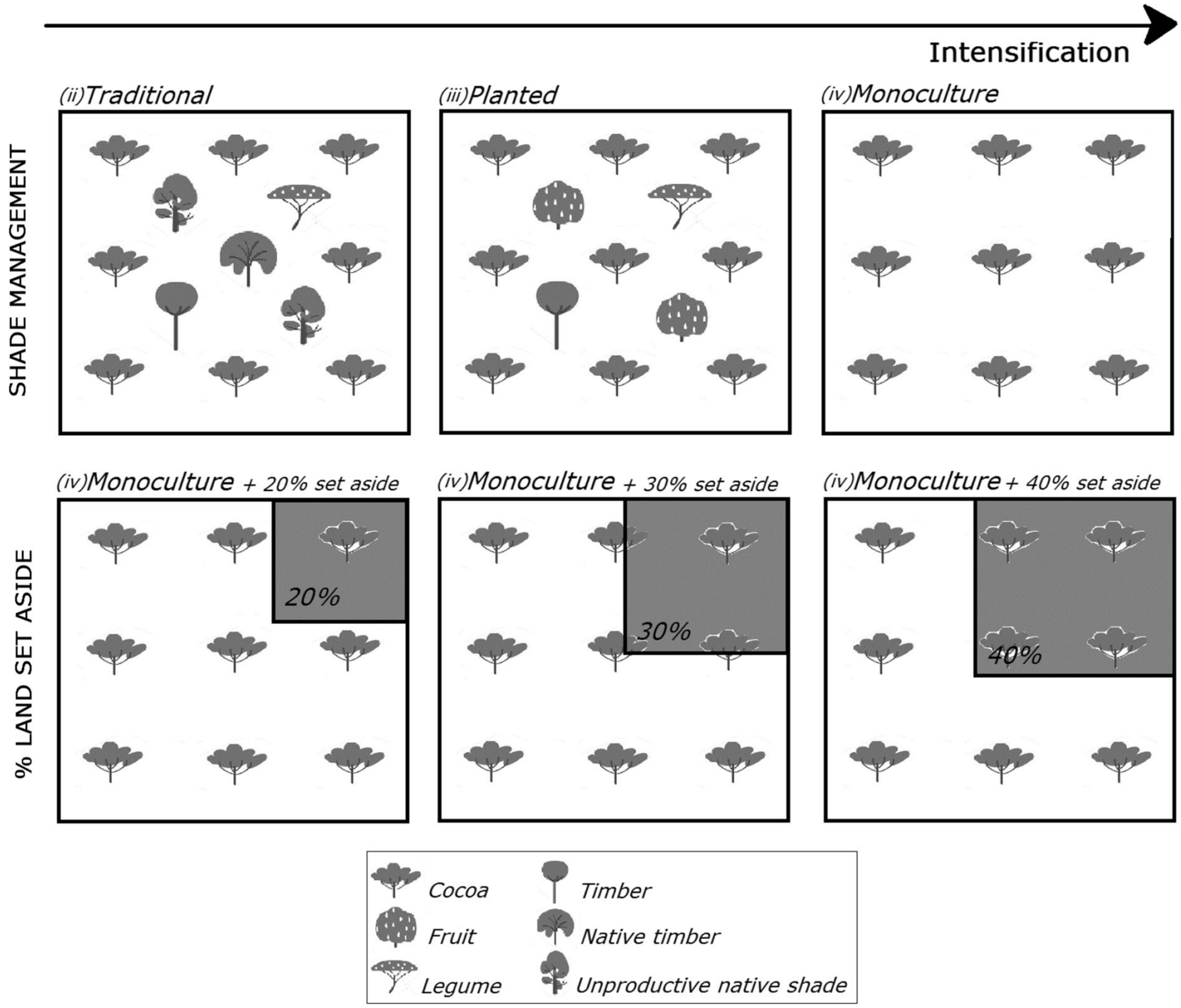

Fig. 2 Schematic representation of the shade management scenarios tested in this study. Scenarios were grouped according to shade management and land set aside strategies along an intensification gradient. Land set aside scenarios (**iv-a**, **iv-b**, and **iv-c**) are indicated with respectively 20, 30, and 40% of agroforestry land cover left for natural regeneration after abandonment (shaded in grey). Different tree icons represent different types of functional groups represented in the LANDIS-II simulations

and monoculture cocoa plantations in Indonesia (Abou Rajab et al. 2016). The partitioning of available carbohydrates among different organs (e.g., fruits, branches, leaves) as a function of total tree biomass is typical for perennials (Niklas and Enquist 2002) and implemented in several physiological growth and production models for cocoa (Beer et al. 1990; Zuidema et al. 2005). Dry bean yield was multiplied by the average farm-gate price for CCN-51 beans and Nacional beans (respectively US$1.93 and US$2.02; SINAGAP 2015; PRAGMATICA 2016) to estimate cocoa revenues per hectare and at the landscape level. We assumed that monoculture plantations exclusively produced CCN-51 beans whereas traditional and planted plantations exclusively produced Nacional beans. In all simulations, cocoa trees were represented by a single functional group (Table 1), neglecting differences in growth characteristics between Nacional and CCN-51 cocoa varieties.

Secondly, we estimated potential revenues from payments for additional carbon stored above baseline levels in carbon markets based on the mean CO_2

Table 3 Description of cocoa plantation management prescriptions for shade management scenarios tested

Pathway description	'Harvest' management prescription (total agroforestry area affected = 88,700 ha/10 years)
(i) Baseline: cocoa farm represent a spatial mix of three shade management types (traditional, planted, monoculture)	In traditional agroforests, remove 10% of all functional group age cohorts. In planted agroforests, remove 70% of functional group 1, 2, 5, and 6 age cohorts; remove 20% of functional group 3 and 4 age cohorts and plant new age cohorts for functional group 3 and 4. In monoculture plantations, remove all functional group age cohorts except cocoa and prevent future establishment of all functional groups
(ii) Traditional: all cocoa farms convert to shade management with naturally regenerating native tree species	At scenario onset, remove 30% of functional group 3 and 4 on previously planted agroforests. Subsequently remove 10% of all functional group age cohorts on all cocoa plantations. Natural regeneration of native shade was allowed
(iii) Planted: all cocoa farms convert to shade management with a planted mix of fruit, legume, and timber tree species	Remove 70% of functional group 1, 2, 5 and 6 age cohorts; remove 20% of functional group 3 and 4 age cohorts and plant new age cohorts for functional group 3 and 4
(iv) Monoculture: all cocoa farms covert to full-sun management (i.e., without shade)	Remove all functional group age cohorts except cocoa and prevent future establishment of all functional groups

Productive shade included both fruit and timber tree species. Harvest management prescription represent percentage of aboveground biomass reduction

storage modeled for cocoa plantations ($CO_2 = AGB * 1.84$). We used a current price of US$5 per ton CO_2 in voluntary carbon markets based on the minimum credit price on the over-the-counter global market for agroforestry projects, which was also the average offset price for Latin America in 2015 (Seeberg-Elverfeldt et al. 2009; Hamilton et al. 2010; Somarriba et al. 2013). Other authors have used lower prices (US$1.2 per ton; Gockowski and Sonwa 2011), but average carbon credits for agroforestry have been increasing to US$9.9 per ton of CO_2 in 2015 (Hamrick and Goldstein 2017). Additionally, we made a second estimate for potential carbon revenues using a hypothetical price of US$30 per ton CO_2, which has been suggested by scholars to cover the social and environmental costs of carbon (Nordhaus 2017) and has been found high enough to incentivize smallholders to maintain shaded agroforestry systems (Seeberg-Elverfeldt et al. 2009).

Landscape metrics

To assess the landscape scale impacts of cocoa plantation management on forest landscape patterns, modeled AGB maps were reclassified for each scenario and time step into 'forested' and 'unforested' cells, using a threshold of 130 Mg per ha AGB (i.e., 65 Mg per ha carbon). Schroth et al. (2015) found that non-cocoa tree AGB stocks above this threshold repressed cocoa yields on cocoa plantations in southern Bahia, Brazil. Average total AGB estimates from the MAE inventories were around 140 Mg per ha (Fig. A2). The resulting binary maps were used to compute four landscape pattern indices calculated for cells classified as forested to capture the effect of shade management on forest fragmentation: (i) percentage of landscape, (ii) number of patches, (iii) effective patch size, and (iv) patch cohesion index, using the R package SDMTools (R Development Core Team 2008; VanDerWal et al. 2014) based on FRAGSTATS statistics (McGarigal and Marks 1995; McGarigal et al. 2012). These indices represented for each scenario respectively the (i) reduction in forested area; (ii) increase in number of forest patches; (iii) decrease in size of forest patches; and (iv) increase in isolation of forest patches. They capture both compositional and configurational landscape heterogeneity, as defined by Fahrig et al. (2011) to describe the variety of cover types and their spatial patterning, which have different on-the-ground conservation implications.

Model assumptions and limitations

General limitations of the LANDIS-II model are the simplification of complex processes and data availability for model parameterization. Knowledge of primary productivity rates remain scarce in the tropics (Malhi et al. 2011; Clark et al. 2013; Zuidema et al. 2013), making the ANPP estimates used in this study a source of uncertainty. We could not control for the influence of climate and soil conditions that are known to influence ANPP (Aragão et al. 2009), due to lack of data. Furthermore, modeling functional species groups makes it difficult to determine if shifts in functional groups abundances would relate to shifts in abundance of rare, forest-dependent, or generalist species in real world landscapes. For example, Kessler et al. (2012) found that transforming natural forest to cacao agroforests led to a significant loss in rare forest-related species richness in 4 plant and 8 animal groups in Sulawesi, Indonesia. We neglected anthropogenic disturbances other than agroforestry management in all scenarios.

To estimate the economic potential from cocoa plantations from simulations, we assumed a linear relationship between increase in total cocoa tree AGB and cocoa fruit biomass. Even though this relation has been applied for physiological production models of cocoa growth, carbon partitioning over different organs depends on several factors, such as water availability and the slope of the allometric distribution function (Beer et al. 1990; Zuidema et al. 2005). Different hybrids and varieties may have different distribution equations, for example storing more biomass in reproductive organs. These differences were accounted for in our estimates by the bean yield to ANPP ratio from Indonesian cocoa plantations (Abou Rajab et al. 2016), but estimates for Ecuadorian plantations were unavailable. Furthermore, the effect of shade management on cocoa yield is still disputed among scholars. Even though many scholars have found that cocoa growth and production decreased non-linearly with increasing shade (Steffan-Dewenter et al. 2007; Wade et al. 2010; Gockowski et al. 2011; Blaser et al. 2017), others have shown that intermediate levels of canopy shade of 40 to 60% protected cocoa trees from drought (Abou Rajab et al. 2016) and allowed to maintain high cocoa production (Waldron et al. 2012).

Results

Model calibration and sensitivity analysis

The LANDIS-II 'spin-up' phase (i.e., biomass initialization prior to simulation onset) estimated 37.26 Tg AGB at the landscape scale with an average AGB for all ecoregions of 107.41 Mg per ha at simulation onset. About 22% of total landscape AGB was allocated in cocoa agroforestry cells. AGB values for LANDIS-II simulations and observed MAE forest inventories were positively correlated (Pearson's correlation = 0.36, n = 172, $p < 0.001$) with a root mean square error of 78.9 Mg per ha at the cell level (Fig. 3). A sensitivity analysis showed that model parameterization was not very sensitive to variations in most key parameter values, indicated by a less than 10% change in total AGB (Table 4). The maximum biomass parameter affected the model outcome the most, with an increase in total AGB at year 50 of about 14% following a 10% initial increase. We kept the initial parameterization for this value given the large number of plots (N = 172) used to determine initial values.

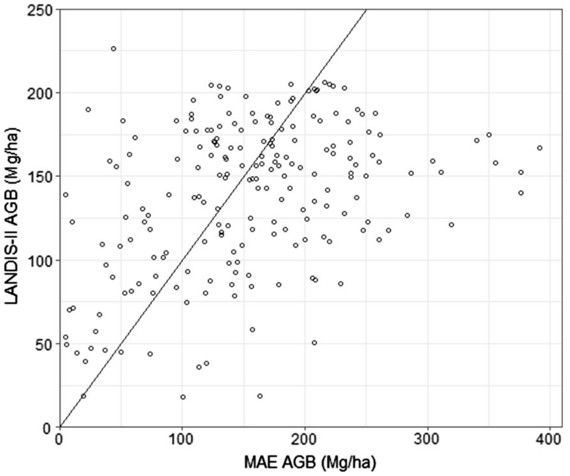

Fig. 3 Estimates of total aboveground biomass for 172 inventory plots collected by the MAE (Ecuadorian Ministry of Environment) against the LANDIS-II spin-up representation of these plots (y-axis). Each plot corresponds to one dot, in contrast with the random communities map used to initialize simulations. The black line corresponds to a 1:1 perfect fit

Table 4 Sensitivity analysis results for six key parameters at year 0 and year 50 for the baseline scenario

Parameter	Change[a]	Year 0		Year 50	
		AGB (Tg)	Change (%)	AGB (Tg)	Change (%)
Baseline scenario	0	37.26	0.00	40.04	0.00
Maximum ANPP	− 10%	35.61	− 4.43	38.38	− 4.15
	10%	38.71	3.89	43.44	8.49
Maximum biomass	− 10%	33.24	− 10.79	36.32	− 9.29
	10%	41.22	10.63	45.72	14.19
ANPP shape	− 10%	37.62	0.97	41.06	2.55
	10%	36.88	− 1.02	39.67	− 0.92
Mortality shape	− 1	36.60	− 1.77	39.38	− 1.65
	1	38.04	2.09	42.41	5.92
Establishment probability	− 10%	37.26	0.00	39.6	− 1.10
	10%	37.26	0.00	41.75	4.27
Shade tolerance	− 1	37.26	0.00	38.35	− 4.22
	1	37.26	0.00	43.70	9.14

[a] Continuous parameters were adjusted 10% and categorical parameters were adjusted 1 unit

Impact of cocoa management on AGB

The absence of natural or anthropogenic disturbances (other than cocoa management) throughout all scenarios allowed for continued forest growth and succession, incrementing AGB stocks (Fig. 4). For the baseline scenario (i), total AGB increased by 7.4% (i.e., 40.04 Tg) 50 years after the spin-up initialization (Fig. 4; Table 5). The removal of all non-cocoa AGB on cocoa plantations in the monoculture scenario (iv) resulted in a 9.1% decrease of total AGB to 36.38 Tg after 50 years (Fig. 4; Table 5). The transition to traditional and planted agroforestry systems resulted in a respective 6.9 and 3.4% increase of total landscape AGB compared to baseline. Setting aside 40% of agroforestry land for natural regeneration could compensate for the loss in landscape AGB following conversion to monoculture systems after 50 years (i.e., monoculture + 40% set aside; scenario iv-c; Fig. 4; Table 5).

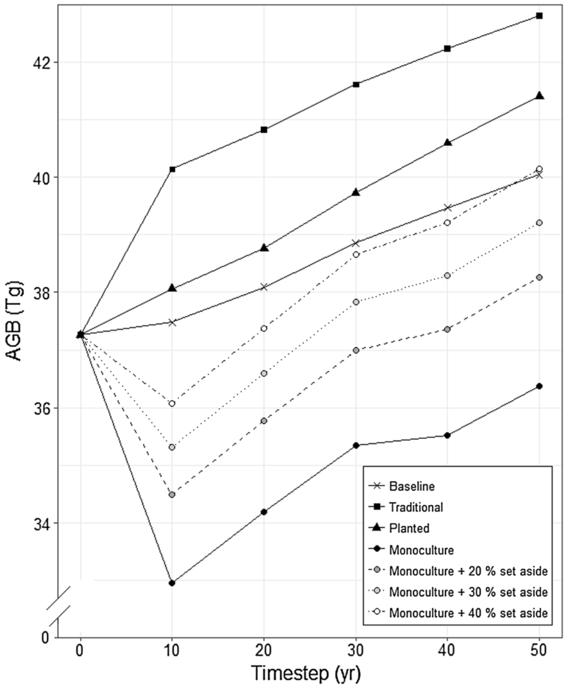

Fig. 4 Total simulated landscape aboveground biomass (Teragram) from onset to year 50 for all scenarios. See Table 3 for scenario descriptions

Impact of cocoa management on functional composition

Shade management affected composition of functional groups strongly at the plantation level (Fig. 5a). In the monoculture scenario (iv), cocoa trees accumulate almost all of the total AGB in plantations. The AGB in the rare functional groups 1, 2, and 6 increased in the traditional scenario (v) relative to the planted and monoculture scenarios, but with a decrease of cocoa AGB (Fig. 5a). At the landscape level, the effect of management scenarios on composition of functional groups was minor (Fig. 5b).

Table 5 Overview of the total AGB scenario outcomes and percentage variation compared to baseline and within scenario change for year 20 and year 50

Scenario	Year 20		Year 50		
	AGB	Change compared to baseline (%)	AGB	Change compared to baseline (%)	Within scenario change from 'spin-up' (%)
Baseline	38.09	0.00	40.04	0.00	7.37
Traditional	40.83	7.19	42.81	6.92	14.80
Planted	38.77	1.79	41.41	3.42	11.05
Monoculture	34.19	− 10.24	36.38	− 9.14	− 2.44
Monoculture + 20% set aside	35.77	− 6.09	38.26	− 4.45	2.60
Monoculture + 30% set aside	36.59	− 3.94	39.22	− 2.05	5.18
Monoculture + 40% set aside	37.38	− 1.86	40.15	0.27	7.67

Total AGB at 'spin-up' (i.e., year 0) equaled 37.26 Tg for all scenarios

Impact of cocoa management on economic potential

Cocoa plantation management affected economic potential during simulations. Estimated revenues from cocoa bean production in the monoculture scenario were 3.5, 5.7, and 7.4 times larger compared to, respectively, baseline, planted, and traditional scenarios (Table 6). Cocoa bean yield estimates from model output were in the range of average yield values for our study region (ESPAC 2014). Compensating for the loss in landscape AGB following conversion to monoculture plantations by setting aside 40% of agroforestry land for natural regeneration resulted in an estimated twofold increase in cocoa revenues at the landscape level compared to baseline (i.e., monoculture + 40% set aside; scenario iv-c; Table 6).

We estimated additional revenues from carbon stored above baseline levels in carbon markets for the traditional and planted scenarios of respectively US$25.7 and US$12.6 million at assumed US$5 per ha per ton CO_2 (Table 6). Summing cocoa and carbon estimated revenues at the landscape scale showed that, at current carbon market price (i.e., US$5 per ha per ton CO_2), the income gap between monoculture and shaded agroforestry systems could not be filled. If carbon market price would rise to US$30 per ton CO_2, a landscape with planted or traditional agroforestry systems would generate, respectively, equal or double revenues compared to a landscape with merely monoculture plantations (Table 6).

Impact of cocoa management on landscape metrics

Landscape pattern indices for the binary forest maps indicated a more fragmented forest landscape for the monoculture scenario (iv), with similar trends compared to the baseline scenario: forested area decreased in combination with low patch cohesion and effective mesh size (Fig. 6). By contrast, the traditional scenario (ii) resulted in a progressive increase in forested area, patch cohesion, and effective mesh size, indicating a decrease in landscape fragmentation compared to baseline. Land set aside for natural regeneration in the monoculture scenarios (iv-a, iv-b, and iv-c) resulted in increased patch cohesion and effective mesh size, indicating increased forest connectivity in abandoned areas (Fig. 6).

Discussion

Impacts of cocoa shade management

Our simulation study found that shade management strategies on cocoa plantations affected AGB stocks, functional group diversity and economic potential at both the plantation and landscape levels. We now discuss these results, keeping in mind that simulations outcomes are not exact predictions.

Aboveground-biomass

We found that plantations with traditional and planted shade management strategies had a large potential to

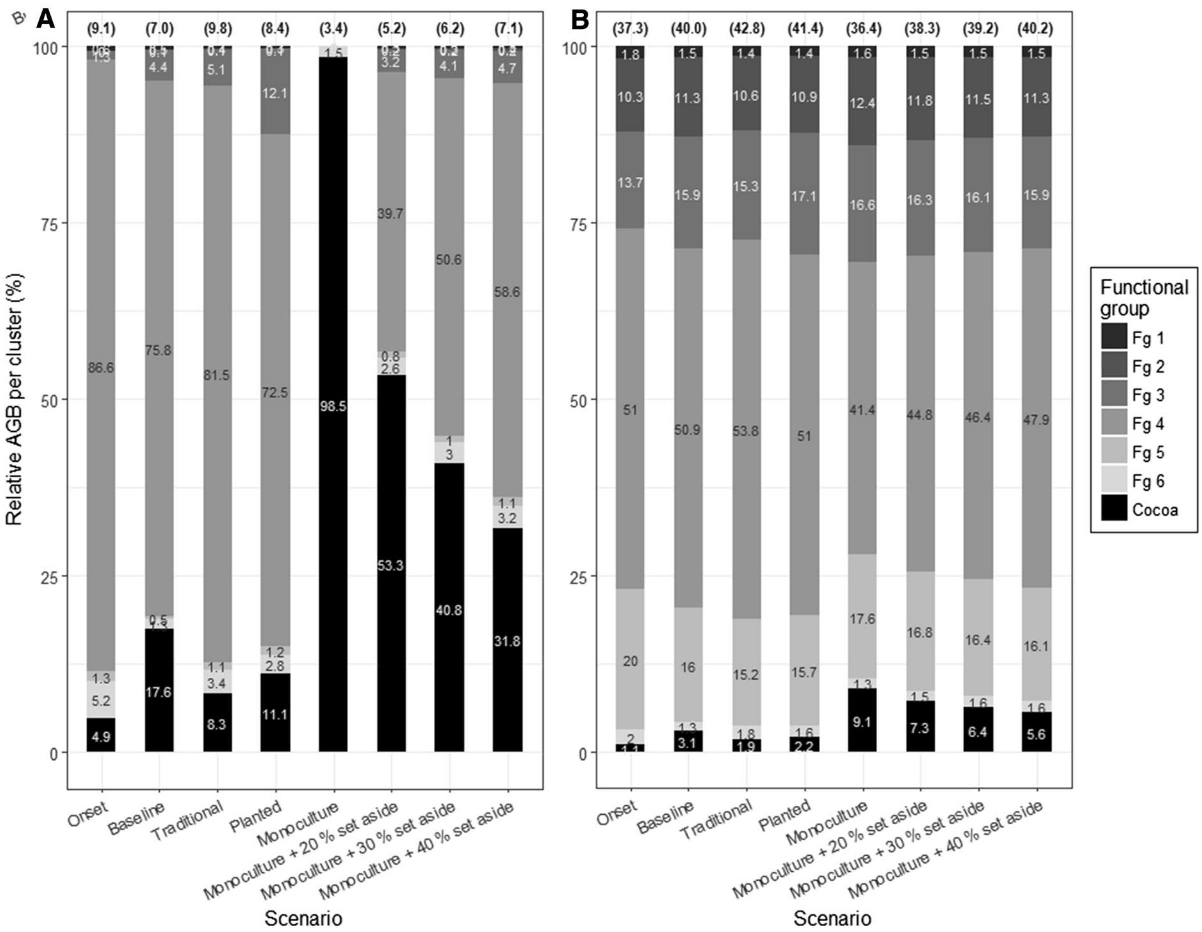

Fig. 5 Functional group composition by aboveground biomass (AGB) at onset ('Current') and at year 50 for the seven LANDIS-II scenarios for **A** agroforestry cells and **B** at landscape scale. Numbers in bars indicate the percentage AGB accumulated in each functional group relative to total AGB; parenthesized numbers above bars indicate total AGB values in Tg

store carbon (resp. 111.3 and 95.3 Mg per ha after 50 years of simulation), storing almost three times more AGB compared to unshaded monoculture plantations (38.3 Mg per ha) (Tables 5, A1). These results were in agreement with previous studies that showed that the level of shading in cocoa plantations affected overall carbon storage potential. For example, in Sulawesi, Indonesia, cocoa plantations with multiple-species shade contained five times more AGB (100 Mg per ha) compared to monoculture plantations (17 Mg per ha) (Abou Rajab et al. 2016). In Ghana, traditional cocoa plantations with more than 25% shade cover stored over three times more AGB than intensified cocoa plantations with less than 25% shade (resp. 262 and 78 Mg per ha) (Wade et al. 2010).

Changes at the plantation level also affected biomass accumulation at the landscape scale, emphasizing the role of agroforestry systems for landscape carbon mitigation efforts. Traditional shaded cocoa management strategies increased the total landscape AGB by almost 7% during our simulations compared to baseline. In southern Bahia, Brazil, over half of the landscape carbon stocks (about 59%) were contained in traditional cocoa agroforests, compared to approximately 30% in natural forest remnants (Schroth et al. 2015), illustrating the critical importance of shaded agroforestry systems for carbon storage.

Table 6 Estimated potential revenues from carbon production (left) and carbon markets at US$5 and US$30 per ha per ton CO_2 above baseline projections (right) for seven shade management scenarios

Scenario	Cocoa production							Carbon markets					
								US$5 ha^{-1} ton^{-1}			US$30 ha^{-}1 ton^{-1}		
	Mean cocoa ANPP (Mg ha^{-1} year^{-1})[a]	Dry bean yield (kg ha^{-1} year^{-1})[b]	Dry bean price (US$ kg^{-1})[c]	Cocoa revenues (US$ ha^{-1})	Cocoa plantation area (ha)	Cocoa landscape revenues (x10^6 US$)	Mean CO_2 plantations (Mg ha^{-1})[d]	Carbon revenues (US$ ha^{-1})[e]	Carbon landscape revenues (x10^6 US$)	Total landscape revenues (x10^6 US$)	Carbon revenues (US$ ha^{-1})[f]	Carbon landscape revenues (x10^6 US$)	Total landscape revenues (x10^6 US$)
Baseline	0.179	136.99	1.98	270.56	88,706	**24.00**	146.81	0	**0**	**24.00**	0	**0**	**24.00**
Traditional	0.085	64.69	2.02	130.68	88,706	**11.59**	204.74	289.62	**25.69**	**37.28**	1737.70	**154.14**	**165.74**
Planted	0.110	84.20	2.02	170.09	88,706	**15.09**	175.32	142.51	**12.64**	**27.73**	855.05	**75.85**	**90.94**
Monoculture	0.653	498.26	1.93	961.64	88,706	**85.30**	70.40	0	**0**	**85.30**	0	**0**	**85.30**
Monoculture + 20%	0.653	498.26	1.93	961.64	70,965	**68.24**	70.40	0	**0**	**68.24**	0	**0**	**68.21**
Monoculture + 30%	0.653	498.26	1.93	961.64	62,093	**59.71**	70.40	0	**0**	**59.71**	0	**0**	**59.71**
Monoculture + 40%	0.653	498.26	1.93	961.64	53,223	**51.18**	70.40	0	**0**	**51.18**	0	**0**	**51.18**

Bold columns indicate the calculated sum of landscape revenues from carbon production (left) and carbon markets (right)

Total landscape revenues represent the sum of cocoa and carbon landscape revenues (in million US$)

[a] From LANDIS-II simulation output over 50 years (i.e., all time steps)

[b] Dry bean yield was estimated by multiplying the mean aboveground net primary productivity (ANPP) in cocoa trees from LANDIS-II simulations with the average dry bean yield to ANPP ratio of 0.76 calculated in Indonesian traditional, planted, and monoculture cocoa plantations (Abou Rajab et al. 2016). Mean dry cocoa bean yield in the area was ~ 252 kg ha^{-1} (ESPAC 2014)

[c] Assuming an average farm-gate price of US$1.93 and US$2.02 per kilogram for respectively CCN-51 (associated with monoculture plantations) and Nacional beans (associated with traditional and planted plantations) in Esmeraldas for 2014 (US$89 and US$93 per quintal; 1 quintal = 46 kg) (SINAGAP 2015; PRAGMATICA 2016)

[d] From LANDIS-II simulation output after 50 years of simulation, assuming Mg CO2 = Mg AGB × 1.84 (Chave et al. 2005)

[e] US$ = Mg CO_2 × US$5 [Mg CO_2]$^{-1}$ for additional carbon stored above the baseline projections

[f] US$ = Mg CO_2 × US$30 [Mg CO_2]$^{-1}$ for additional carbon stored above the baseline projections

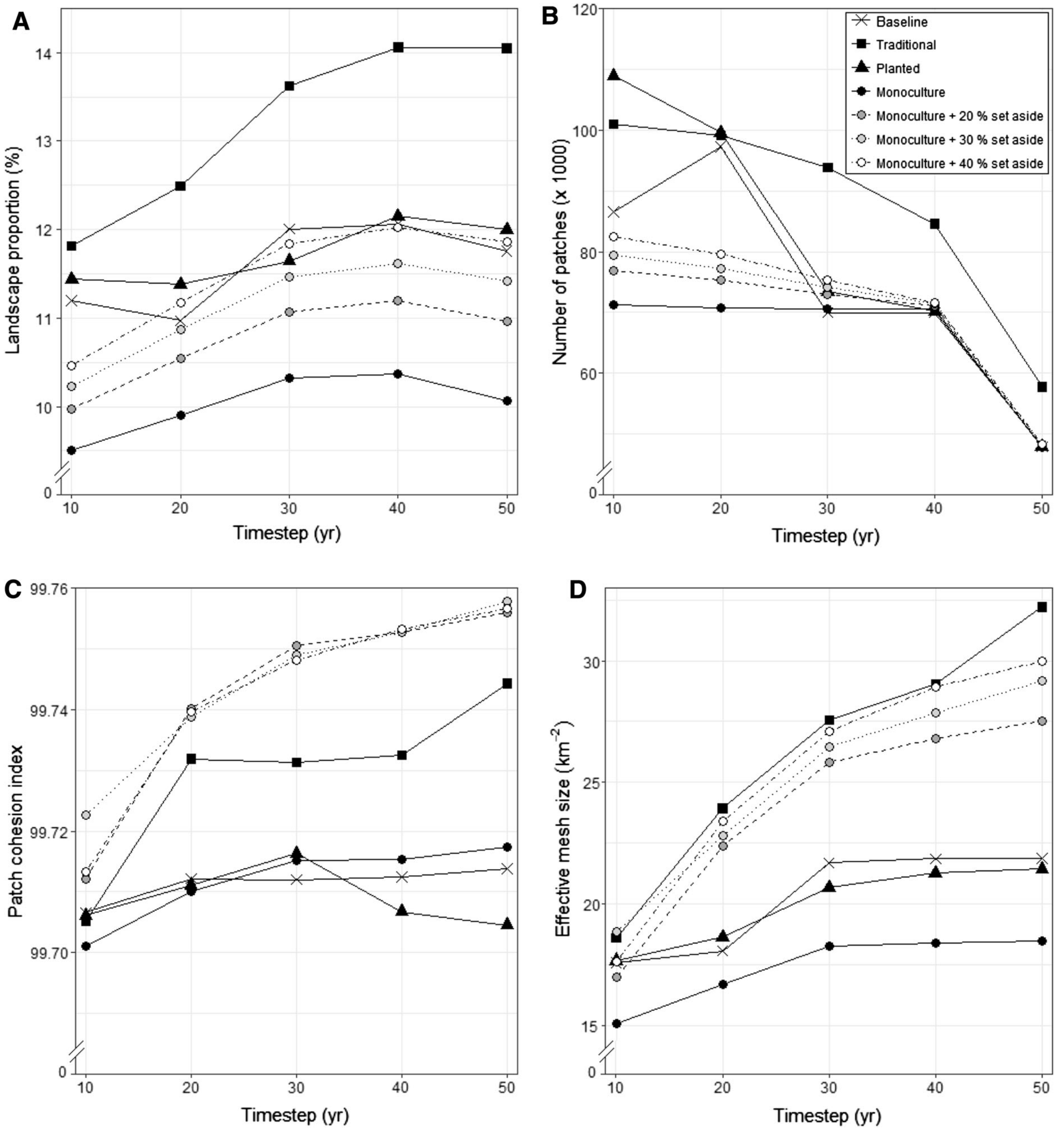

Fig. 6 Landscape pattern indices captured four spatial effects of fragmentation on forest habitat pattern following shade management scenarios simulated in LANDIS-II: **A** reduction in forested area (percentage of landscape); **B** increase in the number of forest patches (number of patches); **C** decrease in size of forest patched (effective patch size) and **D** increase in isolation of forest patch (patch cohesion index)

Biodiversity

We found a shift in functional group diversity at the plantation level following shade management, resulting in small changes at the landscape scale (Fig. 4). Traditional management increased the abundance of rare functional groups, which are absent in monoculture and most planted cocoa plantations. Besides affecting vegetation structure and composition on cocoa plantations (Deheuvels et al. 2012), farmers' management strategies were found to influence beta-diversity of terrestrial plants, epiphytes, amphibians, and soil and litter invertebrates (Deheuvels et al. 2014). For example, the diversity and composition of the vegetation on cocoa plantations has been positively correlated with richness and diversity of bats, birds (Faria et al. 2006; Wilsey and Temple 2011), ants (Bisseleua et al. 2009), soil fauna (da Silva Moço et al. 2009), and mammals (Pardini 2004; Vaughan et al. 2007). The botanical composition of agroforestry systems offers a distinct set of morphological and functional traits, emphasizing the importance of a structurally complex and optimized canopy design. A diverse and structurally complex shade canopy of native species can conserve plant biodiversity on and off-farm by serving as seed source, as well as providing valuable habitats for many other organisms.

Land use strategies also affect the compositional and configurational landscape heterogeneity. In our results, traditional agroforestry systems were associated with more forests that are less fragmented. By contrast, monoculture was associated with less and more fragmented forests. Yet, setting land aside next to monoculture agriculture resulted in greater forest connectivity. Assessing the ecological value of these various land use strategies has to account for the relevance of various habitats to particular species. This requires moving from an evaluation of structural to functional landscape heterogeneity—i.e., evaluating the functions provided by heterogeneity for species of interest (Fahrig et al. 2011).

Economic potential

Our simulations estimated cocoa yield was over seven times larger for monoculture plantations compared to traditional agroforestry systems. The simulated yield gap in our study characterizes yields under optimized conditions, neglecting management constraints—e.g., lack of agricultural inputs, weak management skills. Hence, extensive household surveys on cash income and subsistence needs of cocoa smallholders in Northern Ecuador found smaller yield gaps between shaded and monoculture plantations (Blare and Useche 2013). When discounting for differences in labor costs and market price, Blare and Useche (2013) found profits for monoculture CCN-51 plantations (US$1223 per ha) that were twice as large as for shaded Nacional plantations (US$608 per ha). Even though production revenues are smaller, farmers often prefered traditional production systems due to non-market benefits, such as biodiversity, improved soil quality, and access to food and medicine (Steffan-Dewenter et al. 2007; Blare and Useche 2013; Useche and Blare 2013). An increase in direct profits from shaded agroforestry systems may nevertheless be essential for the maintainance of traditional agroforestry systems. Without additional carbon markets, the simulated yield gap between the baseline and traditional agroforestry scenarios indicated that farm-gate price premiums should double to maintain the economic attractivity of these shaded systems (i.e., about US$400 per ton dry cocoa beans). In 2014, Fairtrade certified beans captured a premium of US$200 per metric ton, whereas premiums for organic, UTZ Certified, and Rainforest Alliance certified beans ranged between US$140 and US$200 per ton (Potts et al. 2014; ICCO 2016).

Our simulations indicated that a landscape planning strategy combining conversion to monoculture systems with about 40% of land set aside for natural regeneration might double total cocoa production while retaining similar levels of landscape aboveground biomass compared with baseline projections (Fig. 5; Table 6). On the other hand, increasing aboveground biomass accumulation on cocoa plantations in shaded management strategies offers smallholders the possibility to participate in carbon markets. We estimated a total additional revenue for traditional and planted agroforestry systems from payments for ecosystem services schemes of US$290 to US$143 per ha at a carbon price of US$5 per ton CO_2. At the landscape level, this current market price did not compensate for lower production compared to monoculture systems. Nevertheless, average carbon credits for agroforestry increased up to US$9.9 per ton of CO_2 in 2015 (Hamrick and Goldstein 2017). We estimated that, if carbon market prices would increase to US$30 per ton CO_2, total revenues from traditional plantations would become almost twice as high as for monocultures. Seeberg-Elverfeldt et al. (2009) estimated that increasing carbon prices up to about US$32 per ton CO_2 would incentivize Indonesian cocoa smallholders to sustain shade intensive agroforestry systems. Recently, agroforestry projects took up only 1% of total carbon volumes covered by global carbon markets (1.3 $MtCO_2e$ in 2009 and 7.5 $MtCO_2e$ in 2015), leaving potential for expansion globally

(Hamilton et al. 2010; Hamrick and Goldstein 2017). Increasing the extent of carbon markets and rising carbon prices is essential to reward smallholders for the environmental benefits their shaded agroforestry systems provide.

Implications and recommendations

Opinions diverge on what forms of agriculture can improve food security while minimizing environmental impacts, from eco-modernism (Asafu-Adjaye et al. 2015) to agroecology (Altieri and Toledo 2011). There is consensus however on the need for smarter landscape management through sustainable intensification (Andres and Bhullar 2016; Fischer et al. 2017). Agricultural diversification, such as multi-cropping and multiple crop rotations, potentially reduces the yield gap with conventional agriculture (Ponisio et al. 2015). Shade canopy optimization for carbon stocks can be achieved by selecting tree species with distinct morphological and functional traits, such as tree species with tall and thick stems, small and light foliage, or rapid growth and high density timber (Somarriba et al. 2013). Besides botanical composition, appropriate spatial arrangement of shade components could improve yield and reduce competition (Deheuvels et al. 2014; Schroth et al. 2016). The maintenance of large trees in agroforestry systems is also a valuable conservation strategy (Schroth et al. 2015) as: (i) they store more biomass and compete less with cocoa trees for light in the understory and (ii) they provide valuable habitat and services for other flora and fauna species (nesting sites, cavities and food, sources of seeds).

Biodiversity-rich areas are often surrounded by a low quality landscape matrix, which results in greater local extinctions. Mixed, small-scale farming systems, like shaded agroforestry systems, may provide an increase in landscape connectivity that can stimulate the matrix quality for many species (Perfecto et al. 2010; Asare et al. 2014). Additionally, agroforestry provides other services that are valued by farmers, such as watershed protection (Garrity 2004), improved pollination (Forbes and Northfield 2017), increased food security and accessibility (Altieri and Toledo 2011; Tscharntke et al. 2012; Kremen 2015), pest, disease, and erosion control (Tscharntke et al. 2011; Smith Dumont et al. 2014), nutrient cycling (Asase and Tetteh 2016), soil fertility improvement (Obeng and Aguilar 2015), and capacity building (Lal et al. 2015). Given the absence of markets for many of these ecosystem services, the economic value of agroforestry systems is largely underestimated.

The landscape-scale context is crucial for the management of agricultural systems (Harvey et al. 2014). Current eco-certification schemes focus on the farm or plantation levels, whereas ecosystem benefits from agroforests are delivered at the landscape level (Tscharntke et al. 2015). To address this scale mismatch, certification mechanisms could be linked with broader landscape-scale approaches (Milder et al. 2014) and consider the landscape as a certified unit (Ghazoul et al. 2009).

Conclusion

Model simulation results show that shade management strategies on cocoa plantations affect AGB stocks, functional group diversity, and economic potential at plantation and landscape levels. Shaded cocoa management strategies, both traditional and planted, increased the total AGB (Fig. 4), preserved functional species diversity on plantations (Fig. 5), and decreased fragmentation of forested areas (Fig. 6), in contrast with unshaded monoculture management strategies. With the current low price for high-quality cocoa beans and carbon payments, smallholders are not sufficiently compensated for the yield gap between shaded and monoculture plantations. Our simulation experiments emphasize the important role agroforestry systems can play for biomass and biodiversity conservation in agricultural landscapes, which underlines the importance of increasing carbon and cocoa bean prices to maintain shaded production systems.

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