Tropical agroforestry and ecosystem services: trade-offs analysis for better design strategies

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Introduction

Agroforestry and tree cover on productive landscapes deliver key provisioning and regulating ecosystem services that improve farmers' livelihoods and aid conservation efforts (Tscharntke *et al.*, 2011; Harvey *et al.*, 2014; Zomer *et al.*, 2014). Agroforestry covers a significant amount of land across several climatic and geographic conditions resulting in a wide range of ecosystem services which requires careful attention to enhance their extent and duration overtime. It is estimated that agroforestry covers between 200 and 357 million hectares in Latin America, including 14–26 million hectares in Central America and 88–315 million hectares in South America (Somarriba *et al.*, 2012). The most prominent agroforestry examples in the region are commercial silvopastoral systems, and shaded tree-crop systems involving coffee (*Coffea* spp) and cocoa (*Theobroma* cacao L.). Currently, agroforestry offers a unique opportunity to achieve the millennium development goals while curving tree cover loss and reducing pressure on remaining forest (Perfecto and Vandermeer, 2010; Kragt and Robertson, 2014).

Recent research provides new insights into the significant contribution of agroforestry to food security, nutrition and conservation of local agrobiodiversity across Latin America. For instance, agroforestry systems (AFS) of coffee and cocoa are important cropping systems that provide goods and services for income generation and family nutrition. Timber production, building materials, fruit consumption and sale, firewood supply and the provision of fiber, honey and medicinal plants are some notable examples (Lopez-Sampson and Somarriba, 2005; Dahlquist *et al.*, 2007; Salgado-Mora *et al.*, 2007; Deheuvels *et al.*, 2012; Almendarez *et al.*, 2013; Cerda *et al.*, 2014; de Sousa *et al.*, 2015). Silvopastoral systems such as live fences and riparian forests aid landscape connectivity and provide shelter for migratory birds, while pastures with medium tree density improve cattle behavior and milk and meat yield, cast shade that enriches grass nutritional value and improve water quality for livestock (Montagnini *et al.*, 2013; Bussoni *et al.*, 2017).

A large body of research has documented a wide list of provisioning and regulating services from AFS throughout the neotropics. So far, carbon sequestration, nutrient cycling, maintenance of water quality/infiltration and enhanced landscape connectivity are the most common and studied services (Jose, 2009; Lin, 2010; Rousseau *et al.*, 2012; Somarriba *et al.*, 2013; Harvey *et al.*, 2014; Lorenz and Lal, 2014). In tropical Latin America, there are many types of AFS with varying design features, plant biodiversity, structure and management regimes, and therefore their performance in providing ecosystem services differ widely in space and over time (Boreux *et al.*, 2013; Rapidel *et al.*, 2015; Mortimer *et al.*, 2017). Furthermore, AFS can exhibit trade-offs between ecosystems services that need to be balanced and reduced to simultaneously offer two or more benefits for farmers in a sustainable way (Mckechnie *et al.*, 2011; Vaast and Somarriba, 2014; Grossman, 2015; Rapidel *et al.*, 2015; Mora *et al.*, 2016; Rahman *et al.*, 2016; Tamburini *et al.*, 2016).

The main objectives of this chapter are to offer an overview of the ecosystem services that the main tropical AFS can offer, and to show the usefulness of several approaches based on the analysis of trade-offs between different ecosystem, and between ecosystem services and plant biodiversity, for better design (or re-design) and management of AFS. This chapter is structured as follows: Section 1 offers an overview of the main provisioning and regulating services provided by five selected AFS (cocoa AFS, coffee AFS, pastures –silvopastoral-, grain fields and home-gardens); Section 2 describes practical approaches to assess trade-offs based on recent scientific literature, and which can be applied in any given AFS; and, Section 3 presents a study case, using data of a so-called Sentinel Landscape El Tuma-La Dalia in Nicaragua, where we applied approaches for trade-off analysis, and based on that we derived recommendations to enhance the delivering of ecosystem services from agroforestry.

Section 1: Overview on ecosystems services provided by tropical agroforestry

AFS provide a wide range of provisioning and regulating ecosystems services at both farm and landscape scale. The quality and extend of those services depend on the arboricultural complexity, species richness, management intensity and the scale of the AFS on the land (Beer *et al.*, 2003; Jose and Bardhan, 2012; Harvey *et al.*, 2014). Notorious examples are given below.

Provisioning services

The shade canopy of coffee and cocoa AFS, dispersed trees in pasture, associated trees in grain fields and home gardens delivers products which significantly contribute to home consumption and sale. For instance, cocoa AFS yield timber and fruits accounting for up to 30% of total annual income for small farmers in Central America (Cerda *et al.*, 2014). The economic contribution of the shade canopy varies according to tree richness and density and the proportion of basal area occupied by shade trees. For example, simple mixed cocoa AFS in Bolivia, produce up to 3 m^3 ha^{-1} $year^{-1}$ of commercial timber (Orozco-Aguilar and Somarriba, 2005). Likewise, cumulative timber stock in 12 years cocoa-*Cordia alliodora* in a lowland of Costa Rica was calculated in 82 m^3 ha^{-1} (Ramirez *et al.*, 2001). In 10 years the over bark stem volume was 128 m^3 ha^{-1} for *C. alliodora*, 97 m^3 ha^{-1} for *Tabebui rosea*, and 172 m^3 ha^{-1} for *Terminalia ivorensis* in AFS (Somarriba and Beer, 2011). Timber stocks in live fences, coffee and cocoa AFS are also significant; for instance, de Sousa *et al.* (2015) estimated the standing volume in the range of 21-87 m^3 ha^{-1}, 18-87 m^3 ha^{-1} and 44-81 m^3 ha^{-1}, respectively. The authors claimed that, despite low timber market prices, the net value from timber sales represents 11–49 % of the total revenue from these AFS. However, this amount could be 58 % higher if farmers were able to improve management practices. In coffee AFS of Nicaragua, Pinoargote *et al.* (2016) demonstrated that the consumption and sale of coffee, fruits, timber, and banana equal the economic returns from high yielding full-sun coffee plantations. Other studies report yields and/or family consumption rates in complex or simple mixed cocoa and coffee AFS that offer key vitamins and mineral (Lopez-Sampson and Somarriba, 2005; Dahlquist *et al.*, 2007; Salgado-Mora *et al.*, 2007; Méndez *et al.*, 2009; Almendarez *et al.*, 2013). Yet, family incomes from fruit sale is limited to the lack of local market channels. Recent research argues that species richness increases income small farmers of eastern Amazonia. It was documented that enriched fallows and multi-strata agroecosystems resulted in higher income:cost ratios and greater satisfaction than pastures and shifting cultivation (Cardozo *et al.*, 2015).

Regulation of pests and diseases

The regulation of pests and diseases is an ecosystem service that biodiversity can provide (Pumariño *et al.*, 2015; Mortimer *et al.*, 2017). However, in the case of AFS, the associated plant biodiversity could have either positive or negative effects on the regulation of pathogens and other undesirable organisms. On one hand, shade trees can hamper noxious pathogens by favoring their natural enemies, by forming barriers to the movement of infectious propagules or pests, and by modifying microclimate of the understory (Beer *et al.*, 1998; Staver *et al.*, 2001; Charbonnier *et al.*, 2017). Trees are also capable of increasing soil nutrients, which is a key function that enhances plant resistance to pests and diseases (Avelino *et al.*, 2012; Tully *et al.*, 2012). On the other hand, shade conditions (especially high dense shade) could favor the development of pathogens including fungi and insects, and some trees and plants could host other pathogens (López-Bravo *et al.*, 2012; Soto Pinto *et al.*, 2012; Cerda *et al.*, 2017a). The reduction of farmer´s dependence on pesticides given the diversity and abundance of insects and natural predators in AFS is another key service that aid the maintenance and improvement of water quality and supply (Gómez-Delgado *et al.*, 2011; Allinne *et al.*, 2016).

Tree species diversity, spatial arrangement and even phenology of associated trees within agroforestry systems may play a role in favoring or limiting biological control of pest and disease outbreaks (Schroth *et al.*, 2000; Sonwa *et al.*, 2002; Perfecto and Vandermeer, 2008). For instance, diversity and clustered rather than regular or random spatial disposition of shade trees negatively affected cocoa yield and favored pathogen pressure in Costa Rican cocoa AFS (Bienga Ngo *et al.*, 2013). Moreover, Opoku *et al.* (2002) reported that some shade trees such *as Funtumia elastica, Sterculia tragacantha, Dracaena mannii* and *Ricinodendron heudelotii* may function as alternative hosts of the cocoa pathogen *Phytophthora megakarya*. In addition, Bisseleua *et al.* (2013) documented that greater species richness of native shade tree species was associated with a higher number of wasp nests and spider webs while species richness of understory plants did not have a strong impact on these beneficial species. Likewise, other authors reported that the number of parasitoid families increased with tree species richness and density in spring and summer, but decreased in winter (Sperber *et al.*, 2004). This result implies that a higher diversity of shade trees will help to maintain high parasitoid levels and, in consequence, higher levels of natural enemies of pests, particularly in the warmer seasons. Finally, other authors argued that high diversity and dimensions of shade trees in traditional agroforest of resulted in a considerable heterogeneity of plot light conditions causing that populations of mirids (*Sahlbergella singularis*) were distributed as pockets in those areas where light transmission was highest (Babin *et al.*, 2010). Overall, the positive or negative effects of shade trees on pest and disease outbreaks will depend on the type of pathogen being assessed and shade canopy structure and management given to both the main crop and trees in the shade canopy. For future studies in AFS, it is suggested to assess primary yield losses (those caused in the current year) and/or secondary yield losses (the reduction of yielding capacity due to negative effects of pests in the previous year) as indicators of regulation of pests and diseases, considered a service given by the structure and plant diversity of the system (Cerda *et al.*, 2017b).

Nutrient cycling and soil quality

Nutrient cycling is a well-researched feature of several AFS. In general terms, it is believed that nutrient cycling is more efficient in AFS than in monoculture because of complementary nutrients uptake, litter deposition, reduced nutrient leaching and improvement of soil quality that enhance roots development (van Noordwijk and Purnomosidhi, 1995; Nair, 2001; Defrenet *et al.*, 2016). A comprehensive review on nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems is presented elsewhere (Hartemink, 2005). Moreover, Seneviratne *et al.* (2010) provides a compilation of the potential, limitations and the effects of plant structure, species richness, spatial arrangement and management practices on nutrient cycling in homegardens. Some notorious examples of cocoa AFS, coffee AFS, homegardens and silvopastoral are given here:

Soil fertility and nutrient cycling in coffee and cocoa AFS has been also well researched across the tropics (Schroth *et al.*, 2001; Pinho *et al.*, 2012; Lorenz and Lal, 2014; Tamburini *et al.*, 2016). The mitigation of nutrient leaching losses is an important ecosystem service which is easily affected by small-scale management decisions. For instance, similar N and P losses at 100 cm were reported between organically and conventionally managed AFS (119 kg N ha−1 yr−1 and 1.5 kg P ha−1 yr−1, respectively) (Tully *et al.*, 2012); however, N losses declined linearly with increasing shade tree biomass, which is determined by farmers. P losses, on the other hand, declined with increasing soil iron pools, which are independent of management decisions. Furthermore, Defrenet *et al.* (2016) reported no significant effect of trees on coffee fine root biomass (coffee root systems comprised 49 % of the total plant biomass in the 1.5 m soil depth) suggesting that coffee root systems are very competitive in the topsoil.

A recent study assessed the ability of shade trees to increase soil carbon stocks and soil fertility and found localized positive effects of individual shade trees on soil carbon and nitrogen content, as well as soil aggregation (Blaser *et al.*, 2017). However, there was no evidence for positive effects of AFS via improved soil fertility or carbon sequestration with increasing shade-tree cover at the plot scale. In a previous study, Isaac *et al.* (2007) reported higher nutrient uptake by cocoa trees under shade (43–80% and 22–45% for N and P, respectively), with K (96–140%) as the most responsive nutrient. Cocoa biomass was also positively affected under low-density shade trees, however, the study cautioned that proper management of upper stratum trees is required for optimum cocoa productivity and effective nutrient cycling. In a subsequent study Wartenberga *et al.* (2017) reported that increase in tree diversity within cocoa plantations did not increase soil fertility parameters in topsoil layers or cocoa yields. The study concluded that in cocoa AFS tree diversification alone may not be an effective solution to mitigate soil degradation after deforestation.

Large amounts of plant litter deposited in cocoa AFS play a key role in nutrient cycling and soil quality. Overall increase of soil organic matter and soil nutrient in improved traditional cocoa AFS was better than in traditional cocoa plantations (Arevalo-Gardini *et al.*, 2015). Rousseau *et al.* (2012) by using a minimum set of four well-accepted abiotic soil quality indicators (bulk density, sum of bases, pH and carbon) were able to separate cocoa AFS plots and forests into five distinct clusters along a low-to-high “soil quality” gradient. The study concluded that cocoa AFS in Talamanca, Costa Rica can conserve soil and provide a high level of soil-related ecological services. Similarly, Silva Moço *et al.* (2008) reported a significant litter layer on the soil of old cocoa AFS and cabrucas (rustic AFS) in Bahia, Brazil which resulted in higher abundance and diversity of soil fauna (2,094 individuals m^{-2} in the litter and 641 individuals m^{-2}). Finally, Pérez-Flores *et al.* (2017) reported that 35-year-old cocoa produced more litter than 55-year-old cocoa (2042 vs 1570 kg DM ha^{-1} $year^{-1}$) and argued that both N–P–K–Ca–Mg contents in litter of 35-year-old cocoa and in litter of 55-year-old cocoa-AFS are enough to recover the nutrients extracted by the cocoa crop.

Carbon sequestration

The potential of several AFS to store atmospheric carbon is the most assessed environmental service across Latin America (Albrecht and Kandji, 2003; Montagnini and Nair, 2004; Nair *et al.*, 2009). Above-ground biomass thus stored carbon has been calculated in coffee and cocoa AFS, silvopastoral systems, home gardens, live fences and riparian forest. Below-ground biomass and soil carbon has been evaluated to a less extent due to presumably the difficulty of capturing mining full data from soil profiles. For instance, Somarriba *et al.* (2013) reported that total carbon stock of Central American cocoa AFS (soil + biomass + dead biomass) was 117 ± 47 Mg ha^{-1}, with 51 Mg ha^{-1} in the soil and 49 Mg ha^{-1} (42% of total carbon) in aboveground biomass (cocoa and canopy trees). The study concluded that stored carbon and sequestration rates in cocoa AFS are significant and similar to those in other cocoa growing regions around the world. Similarly, successional agroforestry systems in Alto Beni, Bolivia had a mean above-ground carbon stock of 143.7 Mg ha^{-1} (± 5.3) with notorious differences among plots depending on the tree diversity and shade canopy complexity (Jacobi *et al.*, 2013). Likewise, Jadan *et al.* (2015) reported that total carbon stocks (aboveground and belowground C) of diversified cocoa AFS in Ecuador were in the range of 85.2 to 141.4 Mg ha^{-1}. These registered values were equivalent to half the stored carbon in near primary forests and three times higher the full-sun cocoa. Rustic cocoa or “cabrucas” in Bahia, Brazil store significant amount of carbon estimated in the range of 87 to 187 Mg ha^{-1} (Schroth *et al.*, 2013). The authors concluded that this rustic cocoa hold 59 % of the total aboveground C stocks of the tree dominated vegetation at landscape scale, while forests hold 32 % and fallows hold 9 %. In a subsequent study, the same authors found that cabrucas with 55% shade level can sustain yield levels up to of 585 kg ha^{-1}, twice the current regional average of 285 kg ha^{-1}, and are compatible with an aboveground C stock in the large shade trees (>30 cm dap) of up to 65 Mg ha^{-1} (Schroth *et al.*, 2014).

Coffee AFS plantations in Latin America also sustain significant quantity of atmospheric carbon in both the coffee shrubs and shade trees. For instance, polyculture-shade organic coffee plots store on average 184.2 (±16.5) Mg C ha^{-1} in living and dead biomass, and soil organic matter (Soto-Pinto *et al.*, 2010). Moreover, carbon storage of coffee AFS with different dominant shading trees, including *Inga* spp., *Pinus* spp. (both 15 years old) and *Eucalyptus* spp. (7 years old) in Villa Rica, Peru were in the range of 119.9 to 177.5 Mg ha^{-1}. Most carbon was fixed in the soil (57–99 %), followed by aboveground tree biomass (23–32 %), tree belowground biomass (8–9 %), coffee shrubs (0.2–2 %) and litter (1 %) (Ehrenbergerová *et al.*, 2015). Contrary as expected, (Noponen *et al.*, 2013) used data from two long-term coffee agroforestry experiments in Costa Rica and Nicaragua to assess the effect on total soil organic carbon (SOC) stocks of (i) organic versus conventional management, (ii) higher versus moderate agronomic inputs, (iii) tree shade types. The study reported that coffee AFS sometimes can function as sinks (Mattsson *et al.*, 2014) or source of soil organic carbon depending on the set of management activities done, type of production systems and shade type.

Homegardens, probably the most ancient, complex and widely used AFS in the tropics, also have a substantial potential to store carbon (Mendez *et al.*, 2001; Kumar and Nair, 2004). Recent research conducted by Saha *et al.* (2009) and Kumar (2011) reveals that the soil C stock was directly related to plant diversity of homegardens in Kerala, India. Overall, within 1 m profile, soil C content ranged from 101.5 to 127.4 Mg ha^{-1}. Similarly, (Mattsson *et al.*, 2014) and Mattsson *et al.* (2013) assessed several homegardens in a dry zone area of Moneragala district, Sri Lanka and reported a mean above-ground biomass stock of 13 Mg C ha^{-1} with a large range among homegardens (1 – 56 Mg C ha^{-1}, n = 45) due tree density and composition among individual homegardens. Total litter production in traditional Mayan home gardens varied from 1,000 to 4,000 kg ha^{-1} yr^{-1} and ten arboreal species were found to contribute more than 33% of total litterfall biomass (Benjamin *et al.*, 2001). Another set of studies highlighted the multifunctional role of homegardens in providing income, food, timber and ecosystem services while decreasing pressure on natural forests and hence saving and storing carbon (Albuquerque *et al.*, 2005; Salinas-Peba and Parra-Tabla, 2007; Whitney *et al.*, 2017).

Water cycling and hydric regulation

The potential of AFS to provide quality water and regulate water balance is one of the less researched topics in modern agroforestry in Latin America. Yet, trees could modify the water cycle by intercepting condense water (and contained nutrients) from clouds, increasing transpiration rates and facilitating water infiltration thus reducing water run-off (Beer *et al.*, 2003; Montagnini *et al.*, 2013). Pioneer research conducted by de Oliveira and Valle (1990) documented that rainfall and throughfall water in cocoa plots shaded by *Erythrina* spp. and *Ficus* spp. in Bahia, Brazil may supply key nutrients to the systems as compared to unshaded cocoa plots. The rainwater contributions of N, Ca, Mg, K, and P reached averages of 43, 21, 9, 9 and nearly 1 kg ha^{-1} $year^{-1}$, respectively. In addition, the average annual throughfall recycling rate to the soil in the shaded plots were 21 kg Ca ha^{-1}, 21 and 12.2 kg Mg ha^{-1}, and 13 and 8 kg P ha^{-1}. The authors concluded that throughfall and leaf fall constitute the most important nutrient recycling processes in the cocoa ecosystem, which appears to be self-sufficient in terms of its nutrient requirements. Interestingly, Poppenborg and Hölscher (2009) documented emergent trees in cocoa AFS tended to reduce rain water input, and produced clear spatial patterns in throughfall distribution since estimated rainfall interception loss was 4% and 16% of Pg in cocoa only and cocoa plus trees plots, respectively. These results suggest that a reduced water availability may lead to reduced cocoa bean yields in times of water shortage. Finally, it was confirmed that the presence of *Inga* trees modifies coffee architecture with shaded coffee plants presenting larger stems and branches resulting in higher coffee funneling ratio under shade. In AFS, coffee plants and trees accounted respectively for 88% and 12% of total stemflow which represented 11.8% of incident rainfall (Siles *et al.*, 2010).

Trees increase hydrologic services in pasture lands, a rapidly expanding land use type across Latin America, and therefore may be a viable land management option for mitigating some of the negative environmental impacts associated with land clearing and extensive cattle ranching (Wassenaar *et al.*, 2007; Montagnini *et al.*, 2013; Benegas *et al.*, 2014). For instance, Bharati *et al.* (2002) reported that infiltration rates were up to five times greater in multispecies riparian buffers than under cultivated fields and grazed pasture, suggesting that pastures with dispersed trees have the potential to increase infiltration and prevent nutrient leaching to groundwater. Likewise, in other study, the tree cover was negatively correlated with runoff (R = -0.71; P=0.01) and positively with infiltration (r = 0.75; P=0.01)(Rios *et al.*, 2008). The study concluded that silvopastoral systems, which have tree components, showed better hydrological benefits in the recharge zone due to a decreased on the runoff and increased infiltration enhancing soil water conservation. After comparing rainfall intensity and frequency data to the measured infiltrability values, Benegas *et al.* (2014) conclude that trees in pasture systems reduce surface runoff at the highest observed rainfall intensities (>50 mm h^{-1}). Finally, in other crops, it was estimated that rainfall interception losses were 6.4% in the polyculture, 13.9 and 12.3% in the peach palm monocultures (*Bactris gasipaes*), respectively, 0.5% in the *Theobroma grandiflorum* monoculture and 3.1% in the fallow (Schroth *et al.*, 1999). With more than 20% of the open-area rainfall, the highest stem flow contributions to the water input into the soil were measured in the peach palm monocultures and in the fallow in central Amazonia.

Similarly, Cannavo *et al.* (2011) documented that runoff was lower in coffee AFS that in monoculture (5.4 and 8.4% of total rainfall, respectively) and a higher water infiltration was observed under AFS. Still, the higher combined rainfall interception + transpiration of coffee and shade trees in AFS resulted in a lower drainage than in monoculture. No coffee water stress was recorded either in SC or MC as relative extractable soil water remained above 20% during the dry seasons. More recently, Padovan *et al.* (2018) evaluated water loss by transpiration and soil evaporation in coffee AFS compared to full sun coffee in sub-optimal environmental conditions and found that AFS were more efficient water user than full sun coffee because a greater proportion of rainfall was used by plant transpiration rather than being lost by soil evaporation.

Likewise, a study of coffee AFS in Southern Mexico (Chiapas, Mexico) conducted to examine the ability of shade trees to maintain water availability in a shade agroecosystem reported that with 60–80% shade cover, daily soil evaporation rates significantly decreased by 41% compared to the low shade site (10–30% shade), although high levels of soil moisture were maintained in the dry season with only 30–65% shade cover (Lin, 2010). The study concluded that the presence of shade cover can reduce overall evaporative demand from soil evaporation and coffee transpiration. Conversely, Abdulai *et al.* (2017) documented that soil water content in full sun is higher than in shaded cocoa (*Albizia ferruginea* and *Antiaris toxicaria*) suggesting that cocoa mortality in the shaded systems is linked to strong competition for soil water. Therefore, promoting cocoa AFS as drought resilient system especially under climate change needs to be carefully reconsidered.

Section 2. Practical approaches to assess trade-offs between different ecosystem services, and between ecosystem services and biodiversity

Balancing production and conservation requires a better understanding of the multiple trade-offs and synergies among ecosystems services to aid design interventions towards resilient agricultural landscapes (Howe *et al.*, 2014; Cordingley *et al.*, 2016; Rahman *et al.*, 2016). There are several approaches to analyze and identify possible trade-offs between indicators of ecosystem services and plant biodiversity in the systems, ranging from exploratory analysis of relationships, correlations, linear and nonlinear relationships, calculation of magnitude of trade-offs, and analysis of services in relation with the allocation of trees in the system. Here below we describe recent practical approaches to assess trade-offs that can be applied to AFS.

Principal component analysis (PCA)

PCA among indicators of ecosystem services, and variables of structure and tree diversity of shade canopies, is useful in order to explore the overall relationships among shade canopy features and among ecosystem services. The position of indicators and variables in a biplot of PCA can reveal whether relationships are positive or negative. This latter then could be denoting possible trade-offs which deserves more attention.

Analysis of Spearman correlations

Spearman correlation analysis between pairs of variables are useful to identify types and levels of relationships (Felipe-Lucia *et al.*, 2014; Tamburini *et al.*, 2016). In the case of agroforestry systems such correlations can be performed between pairs of indicators of ecosystem services, and between ecosystem services and shade canopy features. This analysis provides a first insight of whether positive or negative relationships between two variables are present. Negative correlations denote trade-offs, and the higher the coefficient the higher the trade-off can be between paired ecosystems services.

Linear and nonlinear regressions

Linear and nonlinear regression analysis can be done between original values of pairs of indicators of ecosystem services, and between ecosystem services and shade canopy features (Rapidel *et al.*, 2015; Cerda *et al.*, 2017a). Significant negative relationships would be denoting trade-offs, with the R^2 as an indicator of the strength of the influence of one ecosystem service on the reduction of the other one.

Estimation of the magnitude of trade-offs

There is also another way to analyze relationships between pairs of indicators. Indicators of ecosystem services can be standardized to values between 0-1 to analyze relationships (plots) between pairs of indicators, and then calculate the root mean square deviation (RMSD) as representatives of the magnitudes of the trade-offs (Bradford and D'Amato, 2012; Lu *et al.*, 2014). The higher the RMSD, the higher the trade-off. This approach provides a promising way to visualize trade-offs. Paired ecosystems services plotted closer to the 1:1 line represent the ideal relationship (no trade-offs). Paired ecosystems services plotted far from the 1:1 line indicates otherwise (greater trade-offs) within the agroecosystem (Figure 1). The standardization (0-1) for each observation of indicators of ecosystem services is done as follows (Lu *et al.*, 2014):

$$ESstd = (ESobs - ESmin \,/\, ESmax - ES\,\mathrm{min})$$

where *ESstd* is the standardized value of any ES, *ESobs* is an observed value, and *ESmin* and *ESmax* are the minimum and maximum observed values.

The root mean square deviation (RMSD) is calculated as following (Lu *et al.*, 2014):

$$\mathrm{RMSD} = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (\mathrm{ES}_i - \hat{\mathrm{ES}})^2}$$

where ESi is the standardized value of ESi and ES^ is the expected value of the i number of ESs. RMSD quantifies the average difference between an individual ESstd and the mean ESstd. In a two-dimensional plot, ES^ is on the 1:1 ESs (Figure 1).

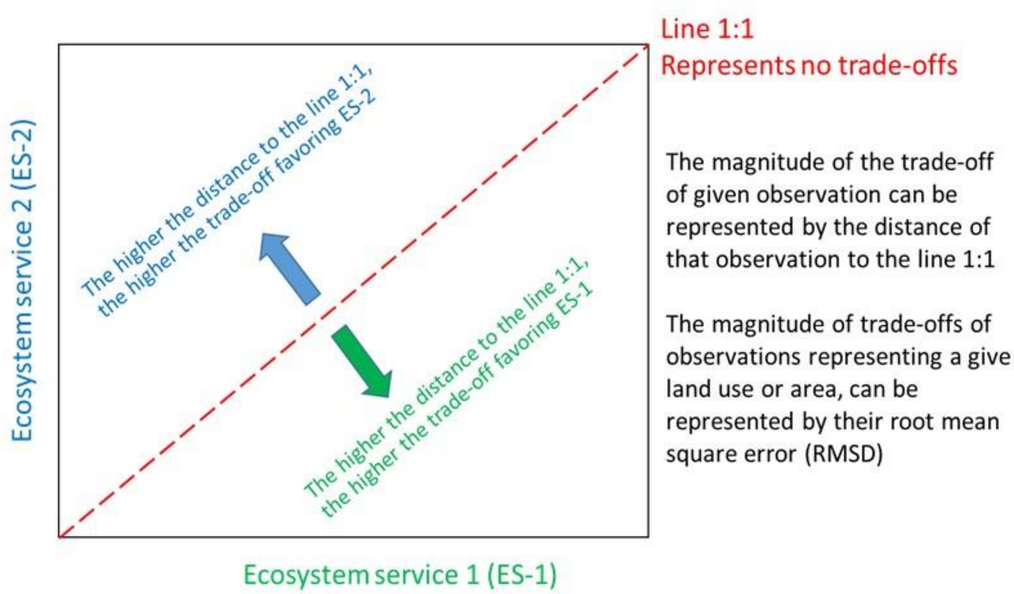


Figure 1. Diagram of trade-off analysis between two indicators of ecosystem services by standardization of ecosystem services values and use of root mean square deviation (RMSD). Source: Bradford and D'Amato (2012) and Lu et al. (2014).

Analysis of allocation of tree basal area in the agroforestry system

Consists on the analysis of the competitiveness between basal area of trees of the main crop and trees of the shade canopy in the agroforestry system (Somarriba *et al.*, 2018). The increase of the presence of a given type of tree can influence the presence of other trees, and therefore influence the quantity of services provided (Figure 2). For instance, a high density and basal area occupied by the main crop may reduce the presence of trees in the shade canopy. Thus, a service provided by the main crop (e.g. production) may be limiting the provision of other service that shade canopy can provide (e.g. carbon sequestration), that way denoting trade-offs. That is why is also worth to analyze the provision of given ecosystem services in function of densities and/or basal areas of different type of trees of the system.

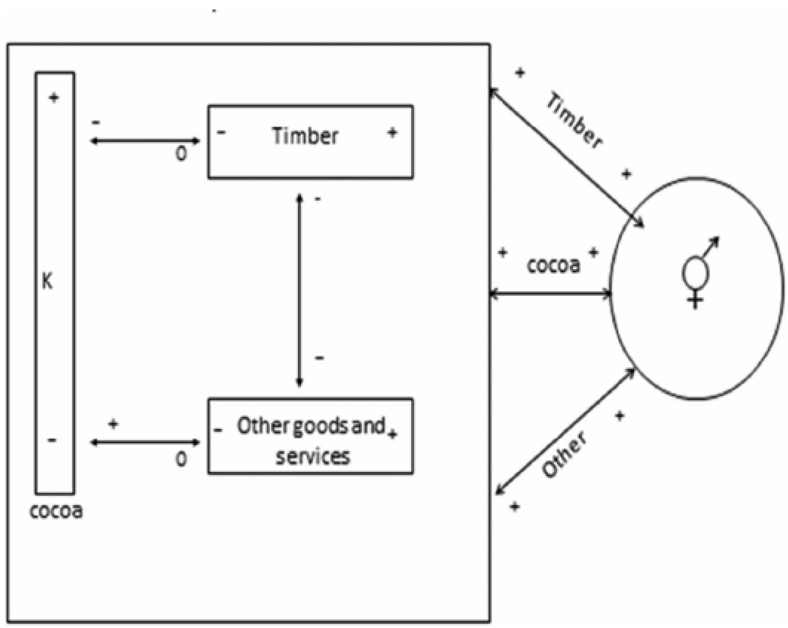
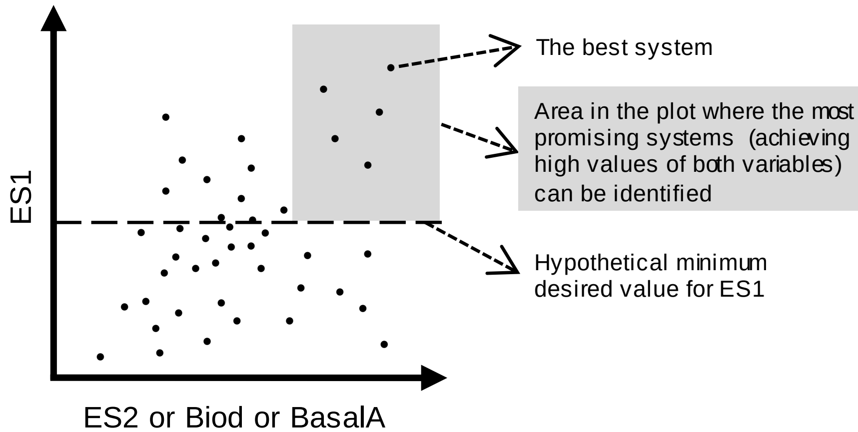


Figure 2. Analysis of competitive allocation of basal areas between tree components of the system that may result in trade-offs. Modified from (Somarriba *et al.*, 2018).

Identification of promising individual systems with the least trade-offs

Apart from identifying trade-offs, it is worth to identify the most promising individual systems (those with least trade-offs and achieving simultaneously desired values of ecosystem services), which could serve as successful models to follow. When plotting in two dimensions, for instance, ecosystem service 1 vs. ecosystem service 2, or ecosystem service vs. biodiversity indicator, or ecosystem service vs. tree basal area of the system, it is also possible to define desired values for the given indicators of ecosystem services, and identify which systems surpass such desired value and at the same time reach good value of the other indicator (Figure 3).



ES1: ecosystem service; ES2: another ecosystem service; Biod: biodiversity in the system; BasalA: basal area of trees in the system

Figure 3. Approach to identify the most promising systems. Modified from (Rapidel *et al.*, 2015; Cerda *et al.*, 2017a).

We believe that the application of all techniques presented above in a given study, will ensure the identification of all possible trade-offs between paired ecosystem services, and between ecosystem services and biodiversity. The integral analyzes of results, will allow to draw tailored recommendations and technical advocacy (on design and management) to balance possible trade-offs in each land use being studied or at a broader scale in a productive landscape composed by several land uses.

Section 3: Study case. Application of trade-offs analysis to derive better management strategies for agroforestry systems

Study site: The Sentinel Landscape El Tuma-La Dalia, Nicaragua.

El Tuma-La Dalia is a municipality of the department of Matagalpa, located in the north center of Nicaragua. El Tuma-La Dalia is part of The Sentinel Landscape Nicaragua-Honduras, where research and initiatives are promoted in order to achieve better management and/or re-introduction of trees at farm and landscape level to increase ecosystem restoration. The landscape of El Tuma-La Dalia is mountainous, where 60% of the land is in slopes and nearly 40% is flat. About 60% of the landscape is fragmented with low forest cover. More than 50% of the land is cultivated in farms whose sizes range from ~0.5 ha - 300 ha, and most commonly smallholders have individual private ownership, and good accessibility. The climate is subtropical, semi-humid forest, with annual precipitation between 2,000 and 2,500 mm. The temperature ranges between 22º and 24ºC. Land use includes mainly cattle ranching, coffee plantations and staple grains, although homegardens and cocoa plantations are also important. All of these land uses have tree components; therefore, we consider all of them as agroforestry systems in the sentinel landscape. They are the main source of income for families, however crop yields are low, due to the impact of diseases (e.g. coffee rust), pests (affecting staple grains), and the alternation of drought and excessive rainfall. Agricultural practices and climate change have taken their toll on the environment: water sources have decreased their flow and are contaminated, and the soils are less fertile. Soils are clayey and loamy clay, with erosion moderate and mostly with agricultural coverage.

Data collection

We used data set from an ongoing project (Forests, Trees and Agroforestry) that assessed tree cover in agroforestry systems of cocoa, coffee, pastures, grains and homegardens in the Sentinel Landscape. This project has generated information regarding provisioning and regulating services from each agroforestry system. We used data of yields of all products produced by the system (not only products from the main crop) to calculate cash flow, value of domestic consumption and family benefit as indicators of provisioning services. We used data of carbon in the above-ground biomass in the shade canopy as indicator of a regulating service. In addition, we selected data about plant diversity (species richness, plant density, basal area) to describe tree canopy structure and reflect the plant biodiversity in the systems. We used these data of 31 cocoa AF, 41 coffee AF, 63 grain fields, 61 pastures (silvopastoral), and 75 homegardens, for a total of 271 plots for this study case.

Shade canopy features and indicators of ecosystem services

Data of the structure and plant biodiversity were obtained through field inventories. Trees recorded in each agroforestry system were identified at species level, and basic measurements such as trunk diameter, tree height and local used were taken. These field inputs allowed us to calculate tree species richness, Shannon index, and tree density and basal area.

We calculated economic indicators (cash flow, value of domestic consumption and family benefit) as indicators of provisioning services, to reflect the overall contribution of the agroforestry systems to family's wellbeing (Cerda *et al.*, 2014; Pinoargote *et al.*, 2016). Economic indicators comprise incomes provided by the main crops as well as other products such as bananas, other fruits and timber. Farm gate prices per product, cultural practices, applied inputs, and production costs (labor and inputs) were obtained through farmers' interview. Calculated economic indicators are described below:

- *GI = AS x MP*
- *CF = GI – CC*
- *VDC = ADC x MP*
- *FB = CF + VDC*

Where: GI = gross income from sale of agroforestry products; AS = amount of agroforestry products for sale; MP = market price; CC = cash costs; CF = cash flow; FB = family benefit; VDC = value of domestic consumption; ADC = amount of agroforestry products for domestic consumption. All results were expressed in United State dollars as USD.

Finally, we quantified aboveground carbon stock in the trees of the shade canopy (not including carbon in the main crops) of the agroforestry systems as indicator of regulating service. Tree inventory inputs were computed and combined with published allometric equations to calculate biomass thus stored carbon for coffee shrubs, cocoa plants and shade trees, dispersed trees in pastures, associated trees in grain fields and tree population in home gardens (Somarriba *et al.*, 2013; Cerda *et al.*, 2014; Andrade *et al.*, 2016; Pinoargote *et al.*, 2016).

Data analysis

We applied all the techniques aimed to identify possible trade-offs between paired ecosystem services, and between ecosystem services and biodiversity described in section 2: PCA, Spearman correlations, linear relationships, magnitude of trade-offs, and relationships with shade canopy features. Biodiversity was represented by Shannon index, and densities and basal areas of different types of trees in the agroforestry systems. Based on the evidences, we derived recommendations to improve the design of agroforestry systems for better provisioning of ecosystem services.

Results

Structure and plant biodiversity in the agroforestry systems of the Sentinel Landscape

The five agroforestry systems within the Sentinel Landscape were contrasting in terms of cultivated area, tree diversity, densities and basal areas. Pastures with trees was the land use with more area per system followed by grain fields, cocoa and coffee AFS with similar areas, and homegardens with the lowest area. Yet, homegardens were the most complex systems as expressed by high densities and tree basal areas (specially fruit trees), followed by coffee and cocoa AFS. Grain fields and pastures had similar characteristics in terms of tree density, basal area and species diversity (Table 1 and Figure 4).

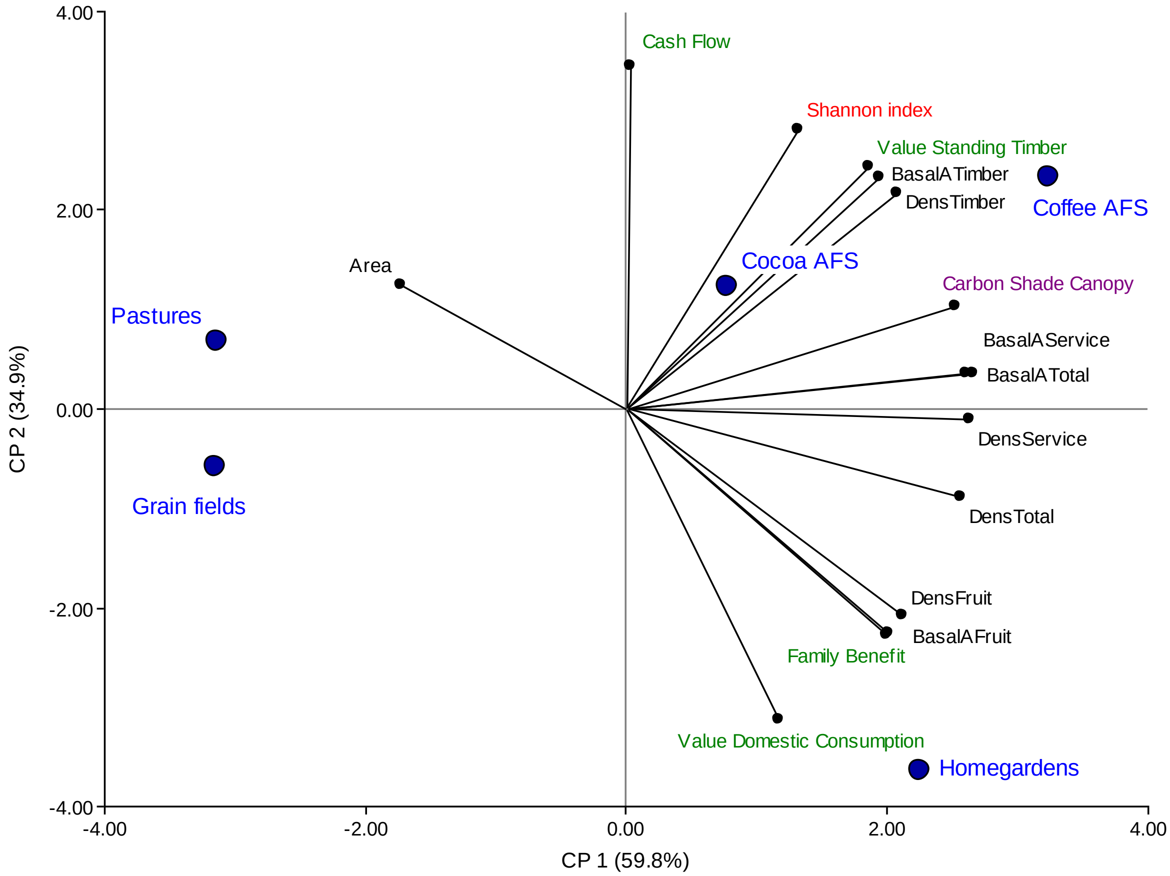
Ecosystem services provided by agroecosystems

Important differences were found between economic indicators (representatives of provisioning services) and carbon stocks (representative of regulating services) among agroforestry systems. Homegardens contributed the most to the overall family benefit, but thanks only to their high domestic consumption. Moreover, cash flow of homegardens was negative on average, which means that most of the whole production is consumed on farm. Both coffee and cocoa AFS registered higher contributions to cash flow than the other systems, and higher value of standing timber, which represents an important family provisioning good for future needs. Grain fields, like homegardens, contributed more to the value of domestic consumption than to the cash flow. Finally, pastures showed the lowest indicators of provisioning in general. Carbon stock was higher in coffee AFS, followed by cocoa AFS, homegardens and least in pastures and grain fields. (Table 2, Figure 4).

Table 1. Structural feature of five dominant agroforestry systems in the Sentinel Landscape, Nicaragua

Characteristics		Cocoa AFS		Coffee AFS		Grain fields		Pastures		Homegardens	
	Units	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Area of the system	ha	1.9	2.5	1.8	1.8	2.0	2.2	8.3	13.5	0.2	0.2
Density of service trees	ind/ha	33.2	28.9	43.6	24.8	8.5	9.5	14.8	11.9	41.7	41.7
Density of posts trees		1.5	3.3	4.5	7.8	0.8	2.0	1.0	2.2	1.8	4.6
Density of fruit trees		35.2	49.0	51.5	55.2	4.8	7.3	6.7	9.8	109.6	88.2
Density of timber trees		38.7	36.1	55.1	45.1	19.6	19.2	22.9	19.2	26.7	30.0
Total density of shade canopy		108.6	85.7	154.7	86.4	33.6	30.1	45.4	29.7	180.1	111.8
Basal area of service trees	m^2/ha	1.7	1.2	2.0	0.9	0.4	0.4	0.7	0.5	1.7	2.2
Basal area of posts trees		0.2	0.4	1.1	3.3	0.1	0.3	0.1	0.3	0.1	0.6
Basal area of fruit trees		1.0	1.6	1.3	1.6	0.2	0.3	0.2	0.3	3.2	3.2
Basal area of timber trees		2.7	2.0	3.8	2.8	1.2	1.7	1.2	0.9	1.4	2.1
Total Basal area of shade canopy		5.5	3.4	8.2	4.1	1.9	2.1	2.1	1.4	6.5	4.7
Total species richness	number	26.4	15.5	31.5	12.2	12.4	6.8	29.6	20.9	12.9	8.5
Shannon index		2.5	0.6	2.7	0.4	1.9	0.6	2.3	0.8	2.0	0.7

SD: standard deviation; ind: individuals; AF: agroforestry systems.



Agroforestry systems are represented by blue circles
Indicators of provisioning services are represented in green
Carbon in the shade canopy is the indicator of a regulating service, and is showed in purple
Shannon index is representative of plant biodiversity in the shade canopies, and is displayed in red
Structural features of tree cover are represented in black

Figure 4. Principal component analysis to explore the relationships among structural features of tree cover and ecosystem services among five agroforestry systems in the Sentinel landscape, Nicaragua.

Table 2. Ecosystem services provided by five dominant agroforestry systems in the Sentinel Landscape, Nicaragua

Indicators of ecosystem services	Cocoa AFS		Coffee AFS		Grain fields		Pastures		Homegardens	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Cash Flow (USD/ha)	426	776	796	953	126	567	226	400	-753	1521
Value of domestic consumption (USD/ha)	529	753	555	663	745	551	223	245	2978	3042
Family Benefit (USD/ha)	955	1035	1351	1123	871	708	449	479	2225	2564
Value of standing timber (USD/ha)	4857	3833	6564	5189	2001	2723	1896	1688	2163	3294
Carbon in the shade canopy (tons/ha)	20	16	36	32	6	5	9	5	22	17

SD: standard deviation; AFS: agroforestry systems

Trade-offs between ecosystem services, and biodiversity

Principal component analysis

This analysis permitted to visualize, in an exploratory way, some possible trade-offs (negative relationships). For instance, trade-offs between cash flow and value of domestic consumption, between cash flow and family benefit, and between plant biodiversity (Shannon index) and family benefit. Shannon index showed positive relationships with carbon in the shade canopy and cash flow. While carbon in the shade canopy showed practically no relationships with economic indicators (Figure 4).

Spearman correlations and linear regressions

We found four significant relationships denoting trade-offs among economic indicators and standing timber, and among economic indicators and plant biodiversity. The value of domestic consumption was negatively correlated with cash flow and with the value of standing timber. Plant biodiversity showed negative relationships with value of domestic consumption and family benefit. No significant relationships were found between economic indicators and carbon in the shade canopy (Table 3). The coefficients of correlation were low in general, therefore according to this analysis the negative relationships would be considered as slight trade-offs. Based on linear regression analysis with paired ecosystem services (similar to Table 3), the same four significant negative relationships ($p<0.05$) were found but with even lower R^2 than the coefficients of spearman, supporting that such trade-offs would be slight.

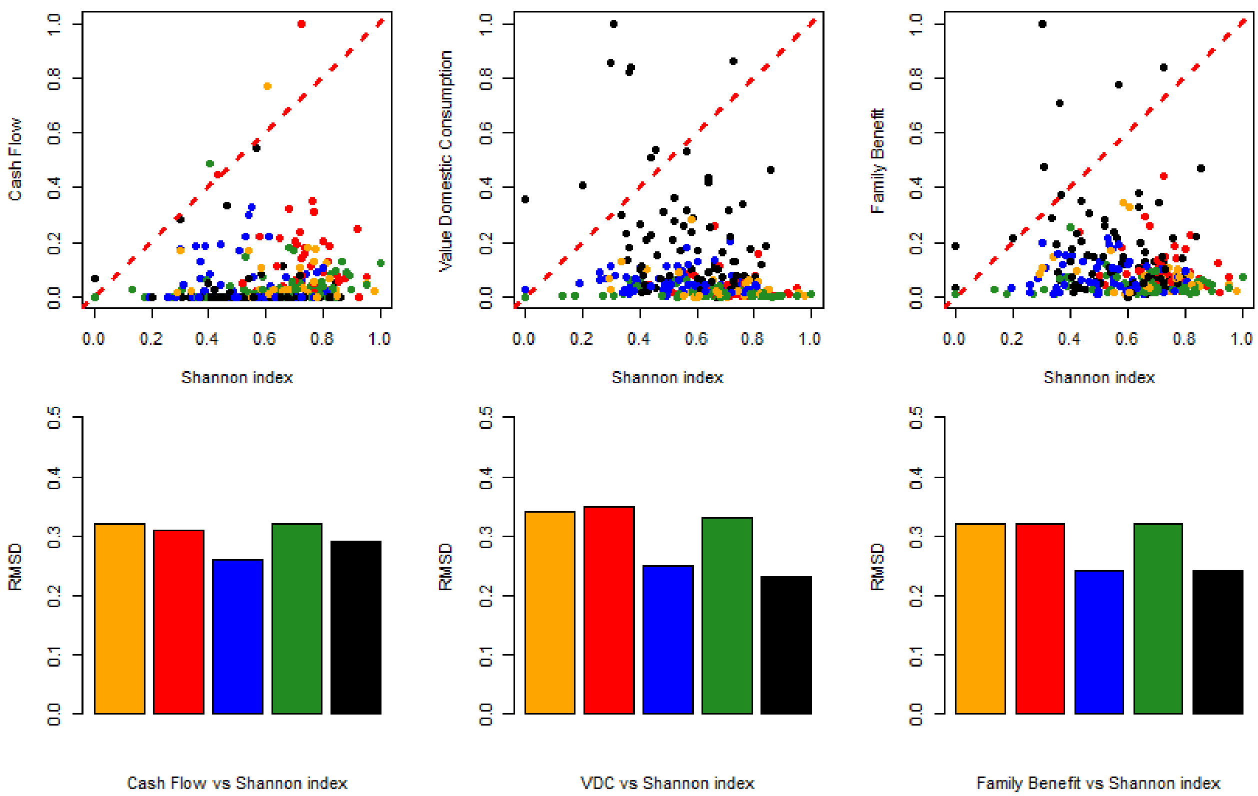
Table 3. Spearman correlations between economic indicators of ecosystem services of five dominant agroecosystems of the Sentinel Landscape, Nicaragua

	Cash Flow		**Value domestic consumption**		**Family Benefit**		**Value standing timber**		**Carbon in the shade canopy**	
	Coef	**p-value**	**Coef**	**p-value**	**Coef**	**p-value**	**Coef**	**p-value**	**Coef**	**p-value**
Value of domestic consumption	-0.41	1.20E-12								
Family Benefit	0.16	0.01	0.74	0						
Value of standing timber	0.35	2.30E-09	-0.12	0.04	0.06	0.35				
Carbon in the shade canopy	0.1	0.12	0.09	0.14	0.24	5.60E-05	0.52	0		
Shannon index	0.27	<0.0001	-0.32	<0.0001	-0.12	0.0398	0.44	<0.0001	0.44	<0.0001

Magnitude of trade-offs

The analysis of relationships using standardized indicators and RMSD revealed trade-offs between economic indicators and plant biodiversity, and carbon stocks. The trade-offs favoring one indicator over another one, and the magnitude of such trade-offs, were different depending on the type of agroforestry system as it is explained bellow.

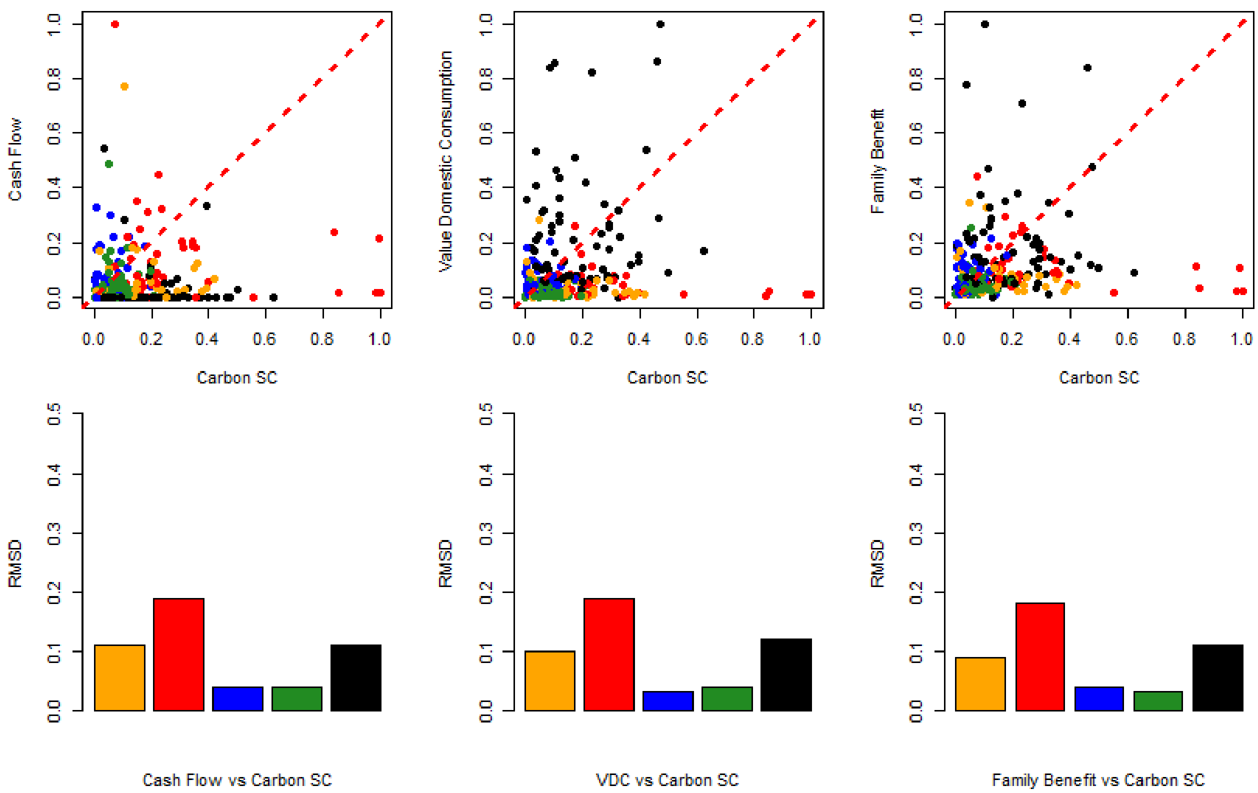
Most agroforestry systems favored plant biodiversity over economic indicators, especially in the case of the relationship with cash flow. The systems with higher magnitude of trade-offs favoring plant biodiversity were coffee AFS, cocoa AFS and pastures. Homegardens showed lower trade-offs and was the only system exhibiting more observations closer to the 1:1 line (the line of no trade-offs) in the relationships of plant biodiversity with value of domestic consumption and family benefit (Figure 5). These are important findings which indicate that in most of the systems such trade-offs occur due to two possible reasons: the tree species of the plant diversity do not provide products for the consumption of the families or domestic animals, nor other products for on-farm uses (timber, firewood, materials) as it would be desired (not useful trees); and/or, farmers are not properly managing their trees, nor taking advantage of the products they could harvest.



Red line is the 1:1 line, which represents no trade-offs.
Points and bars: black: home gardens; blue: grain fields; green: pastures; red: shaded coffee; orange: shaded cocoa. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the greater the trade-off.

Figure 5. Analysis of trade-offs between economic indicators and plant biodiversity (Shannon index) in the shade canopy of five agroforestry systems in the Sentinel Landscape, Nicaragua.

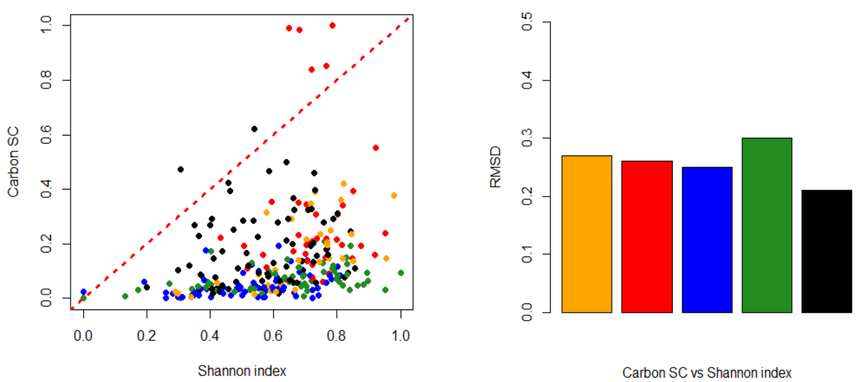
Trade-offs between economic indicators and carbon stocks were notably different depending on the type of agroforestry system. Most coffee AFS, cocoa AFS, homegardens and pastures favored carbon stocks over cash flow, while most of grain fields on the contrary, favored cash flow instead. The relationships with the other economic indicators showed a similar trend, except for homegardens. Approximately half of such systems favored more the value of domestic consumption and family benefit over carbon stocks. In general, the magnitude of trade-offs was higher in coffee AFS, and then in cocoa AFS and homegardens (Figure 6). The magnitude of trade-offs of grain fields and pastures were lower, but it is not an indicator that these systems perform better, because their economic indicators were low. These findings, indicate that, in general, the presence of trees is useful for sequestering carbon but represent an imbalance with the provisioning of incomes and domestic consumption.



Red line is the 1:1 line, which represents no trade-offs.
Points and bars: black: home gardens; blue: grain fields; green: pastures; red: shaded coffee; orange: shaded cocoa. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the greater the trade-off. SC: shade canopy

Figure 6. Analysis of trade-offs between economic indicators and carbon in the shade canopy of five agroforestry systems in the Sentinel Landscape, Nicaragua.

There were also trade-offs between carbons stocks and plant biodiversity. It was clear that all types of agroforestry systems favored more plant biodiversity over carbon stocks. Only few cases of coffee AFS and homegardens were closer to the line 1:1 as reference of no trade-offs (Figure 7). Considering this finding and the others regarding the relationships with economic indicators, it can be said that the evaluated agroforestry systems are contributing to the maintenance and conservation of plant biodiversity (specially trees), but this biodiversity incur in trade-offs with both incomes and domestic consumption, and with carbon sequestration in the current conditions.



Red line is the 1:1 line, which represents no trade-offs.
Points and bars: black: home gardens; blue: grain fields; green: pastures; red: shaded coffee; orange: shaded cocoa. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the greater the trade-off. SC: shade canopy

Figure 7. Analysis of trade-offs between carbon and plant biodiversity (Shannon index) in the shade canopy of five agroforestry systems in the Sentinel Landscape, Nicaragua.

Promising individual agroforestry systems

By applying the approach of identifying individual promising systems (Figure 3), there were very few successful cases among agroforestry systems assessed. Within paired relationship between cash flow and plant biodiversity, only one coffee AFS and one cocoa AFS would be successful. In the case of homegardens, only two cases would be ranked as being successful when family benefit and plant biodiversity (Figure 5) were contrasted. While there were no promising systems to simultaneously achieve high economic indicators and high carbon stocks (Figure 6). Finally, there were five coffee AFS able to reach high carbon stocks with good plant biodiversity values (Figure 7), but they cannot be considered completely successful if they do not contribute importantly to family benefits.

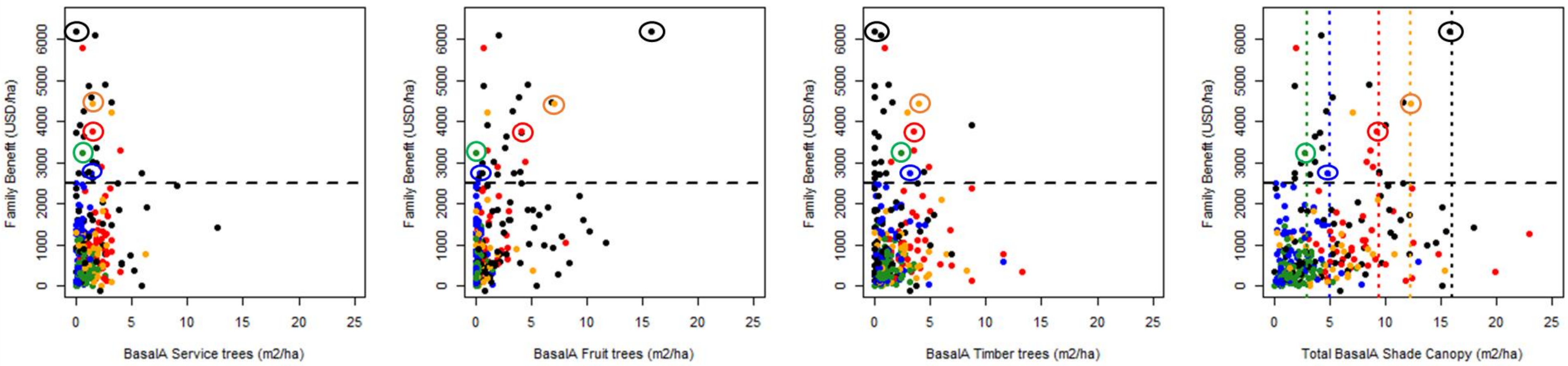
Relationships between ecosystem services and shade canopy features

Based on Spearman correlation analysis, a few significant and negative relationships between provisioning services and shade canopy features were found, denoting trade-offs. It is possible to highlight the negative relationship between cash flow and densities and basal area of fruit trees. There were also negative relationships between value of domestic consumption and family benefit with post trees, but this does not represent a considerable issue given the low density of such trees. Contrary to what was expected, the relationships between value of domestic consumption and family benefit with species richness and Shannon index were negative (Table 4). This latter indicates that plant biodiversity within the five agroforestry systems is leading to trade-offs with the overall expected family benefits. This confirms the findings with the analysis of magnitudes of trade-offs.

Table 4. Spearman correlations analysis between economic indicators of ecosystem services and shade canopy features of five agroforestry systems in the Sentinel Landscape, Nicaragua

	Cash Flow		Value of domestic consumption		Family Benefit		Value of standing timber		Carbon SC	
	Coef	p-value	Coef	p-value	Coef	p-value	Coef	p-value	Coef	p-value
Density of service trees	0.04	0.5198	0.15	0.0131	0.23	0.0001	0.33	<0.0001	0.44	<0.0001
Density of posts trees	0.27	<0.0001	-0.28	<0.0001	-0.12	0.0465	0.21	0.0005	0.24	0.0001
Density of fruit trees	-0.2	0.0008	0.46	<0.0001	0.43	<0.0001	0.18	0.0038	0.53	<0.0001
Density of timber trees	0.22	0.0004	-0.03	0.5762	0.09	0.1623	0.79	<0.0001	0.4	<0.0001
Total density of shade canopy	-0.11	0.0674	0.38	<0.0001	0.4	<0.0001	0.39	<0.0001	0.6	<0.0001
Basal area of service trees	0.13	0.0391	0.06	0.3154	0.18	0.0028	0.45	<0.0001	0.58	<0.0001
Basal area of posts trees	0.21	0.0004	-0.2	0.0012	-0.07	0.2377	0.21	0.0004	0.26	<0.0001
Basal area of fruit trees	-0.16	0.0065	0.43	<0.0001	0.42	<0.0001	0.2	0.0008	0.62	<0.0001
Basal area of timber trees	0.34	<0.0001	-0.1	0.0955	0.07	0.2197	0.98	<0.0001	0.53	<0.0001
Total Basal area of shade canopy	0.06	0.3553	0.24	0.0001	0.34	<0.0001	0.65	<0.0001	0.82	<0.0001
Total species richness	0.37	<0.0001	-0.43	<0.0001	-0.19	0.0021	0.5	<0.0001	0.45	<0.0001
Shannon index	0.27	<0.0001	-0.32	<0.0001	-0.13	0.0397	0.44	<0.0001	0.44	<0.0001

The overall performance of provisioning indicators (family benefit) in relation to basal area of different types of trees for all agroforestry systems in the Sentinel Landscape is presented in Figure 8. In the figures it is possible to see which observations (individual systems) surpass a family benefit of 2500 USD/ha/year, which we consider as a desirable family benefit in the context of that Sentinel Landscape El Tuma-La Dalia. Likewise, it is possible to identify, per each agroforestry system, which observation achieved the maximum value of both family benefit and tree basal area d. For instance, the best paired family benefit and total tree basal area values for pastures, grain fields, coffee AF, cocoa AF and home gardens were 3 m^2/ha, 5 m^2/ha, 9 m^2/ha, 12 m^2/ha, and 16 m^2/ha, respectively (Figure 8). In summary, these will be the maximum values of basal area recommended to manage in each agroforestry system and avoid significant trade-offs. Overall, the approach employed in this study allowed us to better understand the composition of basal areas of different types of trees and their relationships with family benefits provided by trees of successful agroforestry systems.



Points: black: home gardens; blue: grain fields; green: pastures; red: shaded coffee; orange: shaded cocoa.

Horizontal black lines indicate the acceptable value of family benefit considered in this study. Colored circles point to the systems which achieved the highest family benefits of each agroforestry systems.
Vertical colored lines denote the total basal area in the shade canopy of the systems which achieved the highest family benefits of each agroforestry systems

Figure 8. Relationships between family benefit and basal area of different types of trees in the shade canopy of agroforestry systems in the Sentinel Landscape, Nicaragua.

Conclusion and guidelines for balancing trade-offs in agroforestry systems.

The statistical techniques used in this study were useful and complementary among them and aid to identify and support the trade-offs assessment. Principal component analysis was useful to explore the overall relationships among shade canopy features and ecosystem services across agroforestry systems studied. Spearman correlations analysis was suitable to identify the main negative relationships among economic indicators, plant biodiversity and carbon stocks. Standardized ecosystem services indicators of a given agroforestry systems, observations in relationship figures and the RMSD allow the identification of trade-offs, and their imbalances of benefiting given ecosystem services over others, depending on the type of agroforestry systems.

In the study site, in general, most observations across agroforestry systems (coffee AFS, cocoa AFS, grain fields, pastures and homegardens) favored more plant biodiversity and a regulating service (carbon sequestration) over provisioning services (reflected by economic indicators). Such trade-offs need to be balanced in order to obtain higher incomes and overall tangible benefits for the farmers´ families. By doing so, the exploration of economic indicators in relation to tree basal area will help to better identify appropriate levels of basal areas per type of tree that should set as thresholds to simultaneously obtain family benefits and key ecosystem services at landscape level.

Based on the analysis of trade-offs of indicators of ecosystem services and relationships with tree basal area, the following recommendations can be drawn for the studied landscape:

- Across agroforestry systems, grain fields and pastures offered the lowest values of provisioning and regulating services. Therefore, these land uses require more tree-based interventions to increase the overall contributions of tree to both ecosystems services and family benefits.
- Homegardens provided important values for domestic consumption but not for cash flow, denoting a trade-off between those economic indicators. Thus, efforts should be made to promote the cultivation and sale of plant species which offer marketable products to increase family cash flow year-round.
- Contrary to homegardens, coffee AFS and cocoa AFS, need to increase the offer of products for domestic consumption. Such intervention will help create a better balance between family benefit and carbon stocks, and between family benefit and plant biodiversity.
- Within all systems, farmers should be encouraged to plan and properly manage only shade tree species which provide tangible products such as fruits, construction materials, firewood, timber, and medicines for the family, apart from providing shade and/or providing biomass and Nitrogen fixing (like leguminous trees).
- Data from Figure 8 can be considered as a technical advice to make informed decisions regarding the most suitable amount of basal areas per type of tree and total basal area of the shade canopy per each type of agroforestry system.

Actions aimed to reduce of trade-offs and the maximize the overall benefits that agroforestry systems can offer in productive landscapes, apart from contributing to improve farmers' wellbeing, might also reduce the pressure of clearing more secondary and primary forests to increase agricultural production. Therefore, such actions are needed in landscapes like El Tuma-La Dalia which already are fragmented and has low forest cover.

The statistical techniques explained and applied in this chapter are especially useful for suggesting measures to reduce trade-offs and achieve better balances among ecosystem services and plant biodiversity. However, the way to achieve maximization of overall benefits, could be reinforced by techniques aimed to identify and increase synergies. A multidimensional analysis and modelling of synergistic relationships among management (agronomic and agroforestry practices), shade canopy structure and the provision of several ecosystem services, could derive further recommendations to design (or re-design) successful agroforestry systems.

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