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Review

A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry

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ABSTRACT

In tropical regions, the extent of agricultural land is rapidly increasing at the expense of natural forest with associated losses of biodiversity and ecosystem services. Agroforestry has long been proposed as a more sustainable agricultural system, conserving biodiversity and ecosystem services, while providing significant local livelihood. In this context, cacao and coffee agroforestry is often regarded as more compatible with conservation of ecosystem integrity than cacao and coffee plantations. Using meta-analytical techniques and mixed models on data from 74 studies conducted across Africa, Latin America and Asia, a global quantitative synthesis was performed to assess the impact on biodiversity and on ecosystem services of (i) the conversion of natural forest into cacao and coffee agroforestry and (ii) the further intensification of agroforest into cacao and coffee plantation. Forest species richness and total species richness were significantly lower in the more intensively managed than in the more natural land use categories. Response ratios showed that the decline in total species richness was higher when comparing agroforest with plantation (−46%), than when comparing forest with agroforest (−11%). Biodiversity responses to intensification differed between Asia and Latin America, and between different species groups. Response ratios showed that management intensification decreased provision of ecosystem services with 37% when comparing forest with agroforest and with 27% when comparing agroforest with plantation. Our data suggest that species richness decline follows a concave yield function whereas ecosystem service decline follows a more convex yield function. Finally, we identified knowledge gaps related to a conspicuous lack of studies in Africa, and a general underreporting of ecosystem services and environmental variables related to agricultural intensification.

Contents

1. Introduction

Tropical forests are among the most diverse ecosystems on Earth, providing indispensable ecosystem services to the benefit of society (Schröter et al., 2005; Wright, 2005; Gardner et al., 2009). It is currently widely acknowledged that biodiversity plays a significant role in the provision of these ecosystem services (Cardinale et al., 2012; Naeem et al., 2012). For example, more diverse tropical bird communities are more effective in predation of insect herbivores (Van Bael et al., 2008), diverse bee communities in tropical forests enhance pollination of nearby crops (Ricketts, 2004), and more diverse tree communities do produce biomass more efficiently than species poor assemblages (Zhang et al., 2012). Therefore, biodiversity decline through anthropogenic disturbance is expected to jeopardize the ability of tropical forests to sustain ecosystem services essential to agriculture (Hooper et al., 2012).

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Throughout the past century, tropical forests have been subject to dramatic changes due to anthropogenic land conversion, mainly into agricultural land (Lambin et al., 2003; Laurance, 2007). Every year, the area of tropical forest decreases with an estimated 12.3 million ha (FAO, 2010). With an estimated two billion increase of the human population in the next 25 years, mostly in tropical areas, tropical forests and their biodiversity face an uncertain future (Geist and Lambin, 2002). Furthermore, with the scale and impact of agriculture on a constant rise, emerging as a dominant land cover in the tropics, forest biodiversity and ecosystem services will become increasingly affected by the agricultural landscape matrix, surrounding the forests (Perfecto and Vandermeer, 2008; Scherr and McNeely, 2008).

Food production and biodiversity conservation are not necessarily mutually exclusive, however. Tropical agroforestry systems have been proposed as a biodiversity friendly way of agriculture, sustaining both biodiversity, the associated ecosystem services and food production (e.g. Schroth et al., 2004; Steffan-Dewenter et al., 2007). The importance of agroforestry systems in providing ecosystem services such as buffering of climatic extremes and enhancing soil productivity has recently also been documented (Jose, 2009). Shade trees also produce secondary products, including wood and fruits, providing additional income to farmers (McNeely and Schroth, 2006; Tscharntke et al., 2011).

Together, coffee and cacao represent the second largest export products from developing countries and these crops cover a substantial amount of the world's agroforest area (O'Brien and Kinnaird, 2003). Both crops provide income for over 30 million smallholders, mostly in developing countries (Donald, 2004). Cacao (*Theobroma cacao*) and coffee (*Coffea arabica*, *Coffea canephora* and other species within the genus *Coffea*) naturally occur in the forest understory of rainforests in South America and Africa, respectively (Anthony et al., 2002; Motamayor et al., 2002). Exploitation of these crops can range from picking fruits from wild plants in natural forests, to the establishment of intensively managed sun plantations. In traditional coffee and cacao agroforestry, the crops are grown under a more or less dense canopy of various indigenous shade tree species (Sonwa et al., 2007; Perfecto and Vandermeer, 2008). Traditional cacao and coffee management is principally in hands of small scale, community based farmers and it combines sustainable yields with some degree of biodiversity conservation (Moguel and Toledo, 1999). However, fluctuating prices and increasing demand for cacao and coffee on the world market, and increasing local human population pressure, push farmers to intensify the traditional agroforestry management and/or expand the cultivated land area (Laurance, 1999; DeFries et al., 2010). Intensification practices include the recurrent removal of weeds and shrubs, the removal of (slow growing) tree species that are suboptimal for the provision of shade, and the thinning of shade trees (e.g. Schroth and Harvey, 2007; Aerts et al., 2011). The ultimate consequence is the transformation of the natural forest into a plantation with an open and species poor canopy, or no canopy at all (Moguel and Toledo, 1999; Gordon et al., 2007; Tscharntke et al., 2011).

The biodiversity benefits of traditional coffee and cacao agroforestry systems, as compared to plantation cultivation with few or no shade trees, have already received considerable attention from conservation biologists, yet only few of these studies have assessed the impact of agricultural intensification on multiple taxa. Some studies have reported a decline in biodiversity when coffee or cacao management intensifies (e.g. Faria et al., 2007; Gardner et al., 2009; Stork et al., 2009), whereas others have found no overall effect (e.g. Gordon et al., 2007; Steffan-Dewenter et al., 2007). Along with management intensification effects on biodiversity, also the consequences for ecosystem service provision have increasingly received attention. Bisseleua et al. (2009), for example, reported higher insect herbivory when shade cover declined in cacao agroforest in Cameroon. In Ghana, intensification from forest to traditional cacao agroforest, and further to plantations, has been shown to result in a decline in the degree of carbon sequestration (Wade et al., 2010). However, coffee shade plantations with densely planted coffee trees can sequester a high amount of carbon too (Soto-pinto et al., 2010). Attempts to synthesize the effects of management intensification of coffee and cacao agroforestry systems on their ability to conserve biodiversity, and to deliver ecosystem services have been mainly qualitative so far (Perfecto et al., 2003; Schroth and Harvey, 2007; Tscharntke et al., 2011; but see Philpott et al., 2008). A comprehensive meta-analysis across continents, assessing the value of traditional coffee and cacao agroforestry systems for both biodiversity conservation and ecosystem service provisioning, as compared to shaded plantations and natural forests, is lacking. Yet, such a study may help to solve the controversy regarding the value of traditional coffee and cacao agroforestry systems for conservation of biodiversity and ecosystem services. And, as there is no simple trade-off between biodiversity conservation and yield, it may also provide a baseline to the evaluation of economic incentives for local farmers, including certification schemes (Philpott et al., 2007; Bisseleua et al., 2009).

Here, 74 studies across Africa, Latin America and Asia that have reported measures of biodiversity and/or ecosystem services in coffee or cacao agroforestry systems were quantitatively reviewed. More specifically, we addressed the following questions: (i) is there a decline of biodiversity and ecosystem services with increasing management across a forest-agroforest-plantation gradient? (ii) are trends consistent across different continents, taxonomic groups and categories of ecosystem services? and (iii) are trends consistent in coffee and cacao cultivation systems?

2. Materials and methods

Data were collected from the literature found in the ISI Web of Knowledge. A search was performed in February 2012, without restriction on publication year. A list of research articles was generated using combinations of the keywords (*cacao** or *cocoa** or *coffe**) and (*diversity* or *biodivers** or *ecosystem** or *service**). Publications were selected from the retrieved list if they compared species numbers and/or ecosystem services between different land use categories, and also reported the variance or standard deviation of the measurements. We examined publications for measures of species richness in general and, where available, of typical forest species in particular. When species richness was not directly reported, it was calculated from rarefaction or species-accumulation curves provided in the studies. The standard deviations (SD) were calculated from the information provided in the studies. When SD was not provided directly, it was calculated from other variance measures, or derived from the error bars of the provided figures. When studies reported their results only in figures, the raw data were extracted using GetData Graph Digitizer 2.24.

We distinguished between three land use categories: (i) natural forest (hereafter forest), (ii) traditional agroforestry with a stratified and species diverse tree layer (hereafter agroforest) and (iii) plantations with sparse shade trees, belonging to one or very few species (hereafter plantation). Plantations without shade trees ("sun plantations") were not included in our analysis. We relied on the expert knowledge of the authors of each study for assigning the surveyed land use to one of the three defined categories.

For each data record we included information on "continent" (Africa, Latin-America or Asia), "crop" (coffee or cacao) and "taxonomic group" or "ecosystem service category." These variables were used as moderation variables in the meta-analysis. The following eight categories of taxonomic or functional species