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Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest

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ABSTRACT

Human land use has extensively degraded ecosystems, leading to biodiversity losses and reducing the provision of ecosystem services (ES). Agroforestry systems have been recommended as a cost-effective strategy that integrates production and biodiversity conservation, yet few studies have quantified the capacity of agroforestry systems to conserve biodiversity and ES provision. Here we quantify the effects of different types of agroforestry systems on biodiversity and ES in the Brazilian Atlantic Forest. We compared values of biodiversity and ES in different agroforestry systems with those found in conventional production systems and in old-growth forests (reference ecosystem). We assessed 72 studies encompassing 143 study sites and 1700 quantitative comparisons. In general, agroforestry and conventional production systems had lower values of mean effect size for biodiversity and ES provision than the reference systems. However, biodiverse agroforestry systems had higher values of mean effect size for biodiversity and ES provision than simple agroforestry systems and conventional production systems. The use of biodiverse agroforestry systems as an alternative production system reduces biodiversity loss and the negative impact on ES in production areas. Agroforestry systems provide up to 45% and 65% more benefits for biodiversity and ES levels, respectively, than conventional production systems; however, these benefits differ according to the type of agroforestry system. Our findings provide empirical evidence that a biodiverse agroforestry system is the best option to enhance biodiversity and ES in degraded areas where production systems based on sustainable management of natural resources are allowed by law. Our results support environmental public policies focused on environmentally-friendly land management practice and forest landscape restoration techniques.

1. Introduction

Well preserved forests are crucial for biodiversity conservation and ecosystem services (ES) provision (Schroth et al., 2004; Navas and Silva, 2016; Crouzeilles et al., 2016). However, in human-dominated landscapes, protected areas alone are not sufficient to sustain biodiversity (e.g. Crouzeilles et al., 2015). Land use types that combine production and biodiversity conservation as part of a multifunctional landscape, such as agroforestry, are important to minimize biodiversity loss within agricultural landscapes (Torralba et al., 2016). The land management of both productive and protected areas in rural properties (including agriculture, livestock, silviculture, fruticulture, and forest management) must be included in the landscape planning in order to evaluate the effects of production systems on biodiversity, ecological processes, and ES (Laliberte et al., 2010; Lavorel et al., 2011; Alves-Pinto et al., 2017).

Agroforestry systems have been recommended as an environmentally friendly practice and cost-effective strategy of land management for forest landscape restoration (Oliveira and Carvalhaes, 2016; FAO, 2017). This is achieved by reconciling agricultural

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production and biodiversity conservation or enhancement at the landscape level (Rey Benayas and Bullock, 2012). However, there are different types of agroforestry systems (Nair, 1991; Miccolis et al., 2016) that contribute differently to biodiversity conservation and provision of ES. Unfortunately, few studies have quantified differences in the effectiveness of these systems to recover biodiversity and provision of ES in degraded areas (Amador, 2003; Barral et al., 2015; DaRocha et al., 2016; Miccolis et al., 2016; Torralba et al., 2016). Due to the importance of agroforestry as an environmentally friendly alternative production system, it is thus opportune to quantify the factors which influence the levels of biodiversity conservation and ES provision within an agricultural landscape when using this system.

Remote sensing data indicate that globally over 1 billion hectares of agricultural land is used for agroforestry, representing 43% of all agricultural land area on Earth (Zomer et al., 2014). In Brazil, agroforestry systems land area accounts for over 13.9 million hectares (IBGE, 2017). Agroforestry systems became increasingly important in Brazil after changes were implemented in the Law of Protection of Native Vegetation (N° 12.651/2012) (Brancalion et al., 2016), the principal law concerning protection and restoration of native vegetation on private lands (Soares-Filho et al., 2014). According to this Law, the use of agroforestry systems is permitted to recover environmental debts on private rural properties under certain conditions. Environmental debt refers to the non-fulfillment of certain rules of all rural properties in Brazil, regarding the obligation to maintain native vegetation on a percentage of the land as well as in environmentally sensitive areas. Specifically, the use of agroforestry systems is allowed in Legal Reserves (specific percentages of the native vegetation in the rural property that needs to be preserved) and in Permanent Preserved Areas (e.g. river banks, spring and lake surrounds, slopes, hills, and mountain tops) inside small rural properties (Brancalion et al., 2016). Rough estimates suggest an environmental debt of 21 million hectares of native vegetation in Brazil, 78% in Legal Reserves and 22% in Permanent Preserved Areas (Soares-Filho et al., 2014). Therefore, a fundamental question arises: Can agroforestry systems enhance biodiversity and the provision of ES to restore this large amount of land?

This study aims to quantify the effects of different agroforestry systems on biodiversity enhancement and ES provision in agricultural landscapes within the Brazilian Atlantic Forest. We conducted a meta-analysis to evaluate biodiversity and ES values focusing on production areas that have been implemented on land that was previously covered by native forests which was subsequently destroyed. Within these production areas, we compared old-growth forests (used as the reference system) to two types of agroforestry systems and conventional production systems in terms of differences in biodiversity and ES. We describe the extent of the effect of different production systems on biodiversity conservation and ES provision in agricultural landscapes within the study region. We also provide an empirical base to support public policies focused on environmentally friendly land management practice and forest landscape restoration using specific types of agroforestry systems.

2. Materials and methods

2.1. Data collection

First, we conducted an extensive literature review using the SCOPUS, Web of Science, and Google Scholar datasets (Table S1), employing a combination of the following key-words: “Agroforest”, “Agrosilvopastoral”, “Silvopastoral”, “Atlantic Forest”, and “Brazil”. We also conducted the search using the same words in Portuguese. We used the following criteria to select articles: i) studies conducted in the Brazilian Atlantic Forest, ii) studies comparing agroforestry and conventional production systems (agricultural, forestry monocultures, or pasture lands) with old-growth forests (the reference system), iii) studies showing quantitative measures of biodiversity and ES, and iv) studies with replicates for both agroforestry or conventional production systems and reference systems (old-growth forests).

We focused on the Brazilian Atlantic Forest, a biodiversity hotspot (Neto et al., 2016), because this region hosts approximately 120 million people, 70% of the country’s gross domestic product (MMA, 2017), and less than 16% of the forest cover is original (Ribeiro et al., 2009), highlighting the importance of increasing forest cover and leveraging benefits for people (Silva and Tabarelli, 2001; Ditt et al., 2010; Joly et al., 2014). The reference systems were defined according to Crouzeilles and Curran (2016) and Crouzeilles et al. (2016). Agricultural monoculture plantations (including any crop) and monoculture planted forests or pastures were grouped as conventional production systems. We defined an agroforestry system as a land management practice where trees, shrubs, agricultural crops, and animals are used simultaneously or sequentially to produce a large range of products such as timber, fiber, fruits, nuts, annual crops, medicinal plants, and oils (Montagnini, 1992; May and Trovatto, 2008). Agroforestry systems were categorized as simple or biodiverse according to well-established criteria related to the vegetation structure (density, number of layers, and management dynamics), cultivated species richness, and complexity of interactions over time and space (Schroth et al., 2004; Steenbock and Vezzani, 2013; Miccolis et al., 2016) (Table 1).

We retrieved 52 and 521 articles from SCOPUS and Web of Science, respectively. In Google Scholar, we analyzed the first 500 papers that showed up in the search. After removing repetition, we analyzed 947 articles in total. After evaluation of the title and abstract, we downloaded the articles that appeared to match the criteria for a full analysis. We selected 72 articles according to our criteria, from 143 study sites (based on the geographical coordinates of the studies), which contained 1,700 comparisons between agroforestry and conventional production systems with reference systems for biodiversity and ES provision (Fig. 1). Fig. S1 shows the flowchart of the literature used to conduct the meta-analysis.

From each selected article, we gathered the following information: (i) author’s name; (ii) geographical coordinates; (iii) taxonomic group or ecosystem service provided; (iv) type of ecological metrics used to measure biodiversity and ES; (v) quantitative value of the ecological metrics used to measure biodiversity and ES; (vi) number of species used in the agroforestry system; (vii) number of layers in the agroforestry system (the position which a plant occupies in terms of height

Table 1
Criteria used to categorize the agroforestry systems as simple or biodiverse (according to Schroth et al., 2004; Steenbock and Vezzani 2013; Miccolis et al., 2016).

Variables	Biodiverse agroforestry systems	Simple agroforestry systems
Species richness	Five or more species	Less than five species
Number of layers	More than three layers (generally divided into short, medium, tall, and emergent; Vivan, 1998; Yana and Weinert, 2001)	Up to three layers (often dominant, intermediate, and live coverage)
Native and exotic species management	Based on local ecosystems, which use indigenous local species and exotic species with similar ecological function (e.g. Nitrogen-fixing, fast growing species, etc)	May or may not use native species, and crops are usually planted in alley cropping or rows
Successional agroforestry	Uses the local ecological succession throughout the years as a principle, associated with management dynamics and production staggered over time (Young, 2017)	Not based on the local ecosystem and ecological succession

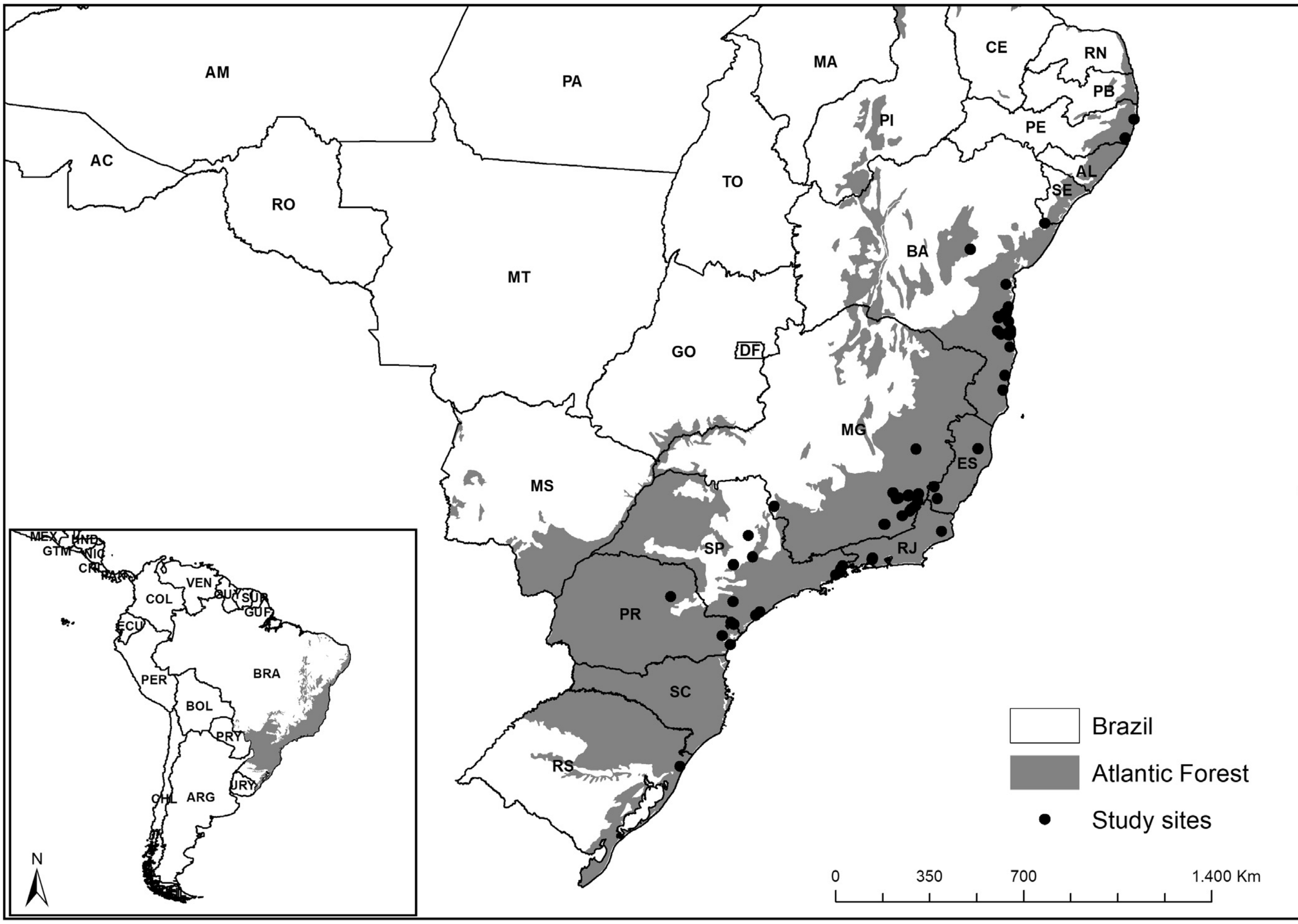

Fig. 1. Spatial distribution of the study sites within the Brazilian Atlantic Forest that were selected for the meta-analysis.

such as emergent layer, canopy layer, or understory layer); and (viii) whether the agroforestry system was based on ecological succession. Biodiversity data were grouped into five broad taxonomic groups: (i) mammals, (ii) birds, (iii) herpetofauna, (iv) invertebrates, or (v) plants. The ecological metrics used to measure biodiversity were: i) species richness, (ii) species abundance, (iii) species similarity, and (iv) species diversity. Data on ES provision were classified as four services: (i) supporting, (ii) regulating, (iii) provisioning, or (iv) cultural (MEA, 2005; Barral et al., 2015). The metrics used to measure ES were related to (i) ecological processes such as nutrient cycling or biological interactions (e.g. microbial activity, leaf decomposition, or CO_2 efflux), or (ii) vegetation structure such as biomass, litter production, or plant density. The production systems were grouped into three categories: (i) conventional, (ii) simple agroforestry system, and (iii) biodiverse agroforestry system (Table 1).

2.2. Statistical analysis

In order to compare different agroforestry and conventional production systems with the reference system in the same study, we used the response ratio, which is a measure of the standardized mean effect size of quantitative measures of biodiversity and ES provision (Borenstein et al., 2009). The response ratio is frequently used in ecological meta-analysis (Nakagawa and Santos, 2012; Koricheva and Gurevitch, 2014; Crouzeilles et al., 2017), and is calculated as the ln ($\bar{x}$ agroforestry or conventional production system/$\bar{x}$ reference system), where $\bar{x}$ is the mean value of a quantitative measure of biodiversity or ecosystem service provision when including all replicates (e.g. Hedges et al., 1999; Crouzeilles and Curran, 2016; Crouzeilles et al., 2016). A negative effect size reflects a lower quantitative measure in agroforestry or conventional production systems than in the reference system, whereas the opposite holds for positive values. An effect size of zero is recorded when the quantitative measure in an agroforestry or conventional production system is equal to the value calculated in the reference system.

A bootstrap procedure was used to avoid spatial pseudo-replication, as some selected studies had more than one quantitative measure for biodiversity or ES provision (e.g. Crouzeilles and Curran, 2016; Crouzeilles et al., 2016). We conducted 10,000 bootstraps using only one comparison in each study to generate the mean effect size and the 95% confidence intervals (Cole et al., 2014). Outliers were removed to achieve normally distributed residuals, which were checked by plotting (Crawley, 2007). The comparison between the reference system and simple or biodiverse agroforestry systems or conventional production systems was performed by evaluating biodiversity, ES provision, supporting, regulating and provisioning services, using five separate analyses. No meta-analyses were conducted for individual taxonomic groups and cultural services due to small sample sizes. All statistical analyses were performed using the software R, version 2.12 (R Development Core Team 2010 - package used was: “plyr”).

3. Results

We found differences in biodiversity, ES provision, and specific ES (supporting, regulating and provisioning) between (i) agroforestry systems or conventional production systems and reference systems; (ii) simple or biodiverse agroforestry and conventional production systems; and (iii) biodiverse and simple agroforestry systems (Fig. 2). In general,

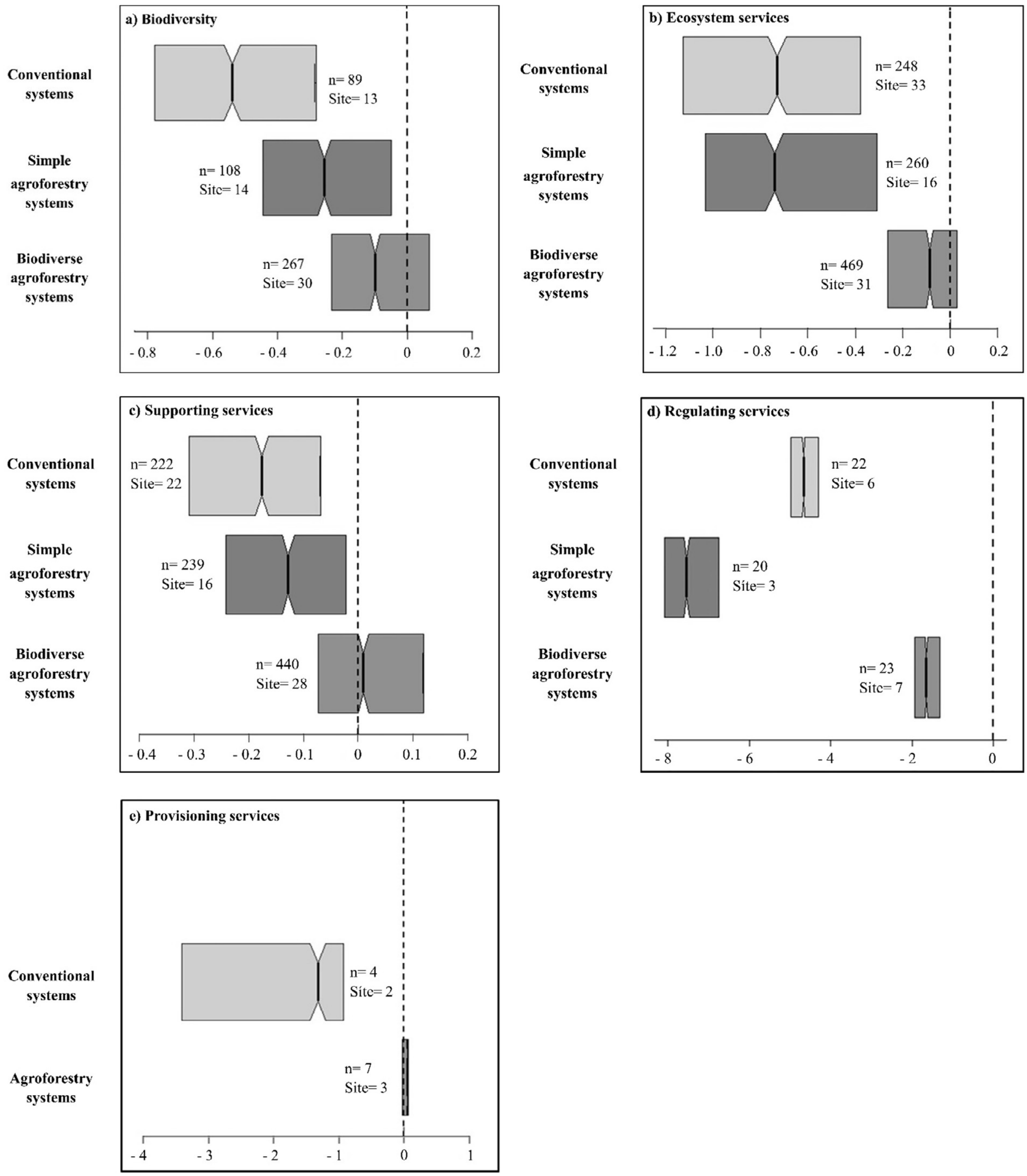

Fig. 2. Bootstrap effect sizes of (a) biodiversity, (b) ecosystem services provision, (c) supporting services, and (d) regulating services for conventional production systems, simple and biodiverse agroforestry systems compared to reference systems in the Brazilian Atlantic Forest. Dashed lines indicate no significant difference with references. n = sample size, site = number of study landscapes. The box plots show the mean effect size, and the variation of the first and third quartile of resampled response ratios. Notches (triangles) in the boxes represent 95% confidence intervals and non-overlapping notches between boxes imply a significant difference (Krzywinski and Altman, 2014; Crouzeilles et al., 2016).

agroforestry and conventional production systems had lower values of mean effect size of biodiversity, ES provision, and regulating services than reference systems (Fig. 2a, b, and d). For supporting services (Fig. 2c), the same is true for simple agroforestry and conventional production systems, but not for biodiverse agroforestry systems. Values of supporting services did not vary between biodiverse agroforestry and reference systems (Fig. 2c). Values of mean effect size of biodiversity, ES provision, and regulating services were 10–18% lower in biodiverse agroforestry systems than in the reference systems (Fig. 2a, b, and d). Due to small sample sizes, we grouped both agroforestry systems types in one single category (agroforestry) for provisioning services (Fig. 2e). For those services, the conventional production systems also had lower values than reference systems (−132%), while agroforestry systems had higher values of provisioning services than reference systems (5%).

Nonetheless, the mean effect sizes of biodiversity, ES provision, supporting services, and regulating services were higher in biodiverse agroforestry systems than in simple agroforestry systems and conventional production systems (Fig. 2). In biodiverse agroforestry systems, values of biodiversity, ES provision, supporting services, and regulating services were 15%, 62%, 17%, and 570% higher than in simple agroforestry systems, and 45%, 65%, 12%, and 280% higher than in conventional production systems, respectively. Simple agroforestry systems had higher mean effect sizes of biodiversity (30%) and supporting services (5%) when compared to conventional production systems (Fig. 2a and c); however, no difference was found for ES provision (Fig. 2b) and lower values were found for regulating services (290%) (Fig. 2d).

4. Discussion

Overall, our results highlight the influence of the type of agroforestry system over the maintenance of biodiversity and ES provision in the Brazilian Atlantic Forest. They show the same pattern observed in a meta-analysis conducted in Europe, where agroforestry systems have a significant positive effect on biodiversity conservation and ES provision when compared to conventional systems, specifically in relation to nutrient cycling (supporting services), biodiversity, and erosion control (regulating services) (Torralba et al., 2016). From an applied perspective, these similar results highlight the fact that agroforestry systems are an alternative method to recover degraded lands in human-dominated landscapes and can reconcile production and conservation. Agroforestry systems are structurally and functionally more complex than silvicultural and agricultural monoculture plantations; having a higher vegetation structure diversity contributes to nutrient cycling, erosion reduction, and the enhancement of biodiversity without compromising productivity (Nair, 2007).

However, in agroforestry systems, the provision of ES and the recovery of biodiversity differ depending on the type of system. Our findings show that biodiverse agroforestry systems can potentially maintain higher levels of biodiversity and ES provision when compared to simple agroforestry systems. Hence, the use of biodiverse agroforestry systems instead of other production systems enhances the ability of the agricultural landscape to have less negative impact on biodiversity as well as increase ES provision. They can be used as an alternative method to recover degraded areas where production systems based on sustainable management of natural resources are allowed by law, such as in the Brazilian Atlantic Forest (Brancalion et al., 2016) or in African countries such as Mozambique (Chiziane et al., 2015), Niger and Ethiopia (Reij and Garrity, 2016), or other South American countries such as Peru (Robiglio and Reyes, 2016) and Colombia (Calle et al., 2013). Within an international context, recent studies from FAO, CIFOR and the World Agroforestry Centre supports the use of agroforestry for landscape restoration in the world (FAO, 2017), as well as regionally, in Latin America (Schweizer et al, 2018) and Central Asia (Djanibekov, et al., 2015). Another good example is the UN Reducing Emission from Deforestation and forest Degradation (REDD +) scheme, which also supports the use of sustainable land management practices to mitigate climate change. In addition, biodiverse agroforestry systems can be more profitable than simple agroforestry and conventional production systems (Miccolis et al., 2016). Summing the net value until the 10th year, profit in simple agroforestry systems ranges from US$ 347–15,469/ha (exchange rate of 1 US$ = 3.24 BRL in 2017), whereas it ranges from US$ 27,781–38,200/ha in biodiverse agroforestry systems (Miccolis et al., 2016). Thus, the challenge of scaling up biodiverse agroforestry systems must be better assessed and addressed through specific environmental public policies.

Policies focused on environmentally-friendly land management practices and forest landscape restoration should advocate for the use of biodiverse agroforestry systems. As an example, in Brazil, where the Law of Protection of Native Vegetation allows the use of agroforestry systems to recover environmental debts in private rural properties, we recommend that biodiverse agroforestry systems are used instead of simple agroforestry systems. In such cases, care must be taken when choosing the groups of species and management dynamics to be used in the agroforestry systems in order to maximize the ecological benefits.

Our results revealed that agroforestry systems are more depleted than reference systems with regard to biodiversity and ES provision, but that the extent of this depletion depends on the type of agroforestry system. For provisioning services, the results revealed higher values for agroforestry systems than in reference systems (5%). Furthermore, we highlight that more studies measuring indicators of provisioning services comparing agroforestry systems with native forests are needed. However, it is important to emphasize that previous meta-analyses also highlighted that biodiversity tends to be lower in restored systems than in reference systems (Crouzeilles et al., 2016; Meli et al., 2017; Crouzeilles et al., 2017). From a forest landscape restoration perspective, the main goal is restoration of the functionality of ecosystem processes through multifunctional landscapes, which also enhance human well-being (Lamb et al., 2012; Sabogal, et al., 2015). This study corroborates the finding that agroforestry systems, especially biodiverse systems, can contribute to recovery processes at a landscape scale (Baah-Acheamfour et al., 2014; Navas and Silva, 2016; FAO, 2017). Therefore, it is paramount to integrate well preserved forests (most of them located in public protected areas) with agroforestry systems within the agricultural landscapes (which are located in private lands), resulting in a mosaic of land use types that combine both biodiversity conservation and provision of ES, including crop production.

5. Conclusions

Well-preserved forests should be conserved and expanded because of their unique capacity to maintain biodiversity and ES provision in the long-term (Crouzeilles et al., 2016). Nonetheless, adopting more environmentally friendly land management practices in agricultural landscapes is a good complementary strategy. From a production system perspective, biodiverse agroforestry systems are most similar to reference ecosystems in terms of biodiversity conservation and ES provision. Our results strongly support the use of agroforestry systems, especially biodiverse systems, for recovery of degraded landscapes and as a more environmentally friendly land management practice. Implementation on a large scale would be easier if specific environmental public policies existed (FAO, 2013) and if research efforts focused on agroforestry research "in" development instead of "for" development (Coe et al., 2014). In Brazil, for example, the Law of Protection of Native Vegetation should be more specific in terms of which type of agroforestry system is more appropriate to recover a forest debt that encompasses more than 20 million hectares (Soares-Filho et al., 2014).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2018.10.064.

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