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Silva-Galicia, Ana; Valencia, Vivian; Arroyo-Rodríguez, Víctor; Ceccon, Eliane

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Weight-of-evidence approach for assessing agroforestry contributions to restore key ecosystem services in tropical dry forests

Ana Silva-Galicia · Vivian Valencia · Víctor Arroyo-Rodríguez · Eliane Ceccon

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Abstract Worldwide deforestation and degradation are limiting the capacity of tropical dry forests (TDFs) to provide environmental services. Agroforestry systems (AFSs) are agricultural land systems that combining perennial elements with crops, can provide important benefits to people (e.g. timber and non-timber products) and the environment (e.g. hosting biodiversity). Using a semi-quantitative methodology (i.e. weight of evidence), we assessed the role of the three main types of AFSs (intercropping, multistrata and silvopastoral and protective systems) in restoring key ecosystem services in TDFs. We found that each type of AFSs contributed differently to soil quality restoration, productivity, biodiversity, carbon sequestration, and culture preservation. Yet, AFSs can also deliver few disservices, such as yield reductions. Despite the identified knowledge gaps, such as the carbon sequestration capacity, our findings indicate that AFSs can contribute to restore TDFs by providing valuable ecosystem services to halt degradation and sustain people's livelihood.

Keywords Intercropping systems · Multistrata systems · Silvopastoral and protective systems · Soil quality improvement · Production increase · Cultural importance

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A. Silva-Galicia
Posgrado en Ciencias Biológicas, Facultad de Ciencias, Universidad Nacional Autónoma de México, Av. Universidad 3000, Circuito Exterior s/n, CP. 04510 Coyoacán, Mexico City, Mexico
e-mail: silvagalicia.al@gmail.com

V. Valencia
Farming Systems Ecology Group, Department of Plant Sciences, Wageningen University and Research, Droevendaalsesteeg 1, 6708PB Wageningen, The Netherlands
e-mail: vivian.valencia@wur.nl

V. Valencia
Department of Environment, Agriculture and Geography, Bishop's University, 2600 College St, Sherbrooke QC J1M 1Z7, Canada

V. Arroyo-Rodríguez
Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Antigua Carretera a Patzcuaro 8711, Ex-Hacienda de San José de La Huerta, 58190 Morelia, Michoacán, Mexico
e-mail: victorarroyo_rodriguez@hotmail.com

E. Ceccon (✉)
Centro Regional de Investigaciones Multidisciplinarias, UNAM, Av. Universidad s/n, Circuito 2, Col. Chamilpa, 62210 Cuernavaca, Morelos, Mexico
e-mail: ececcon61@gmail.com

Introduction

Deforestation and forest degradation are increasing threats in tropical dry forests (TDFs), which have been considered the most threatened tropical forests worldwide (Blackie et al. 2014). These anthropogenic disturbances limit the maintenance of human wellbeing, a major concern, considering that TDFs support a significant portion of the poorest people in the world (Djoudi et al. 2015), who rely on forest resources and agriculture for their livelihood (Mbow et al. 2014; Djoudi et al 2015). Thus, understanding how to restore at least some elements of the structure and function of TDFs while also covering people needs is an urgent task (productive restoration; Ceccon 2013).

Agroforestry systems (AFSs) are land-use systems where crops and/or pastures coexist with perennial elements (trees, palms, bamboo, cacti or rosetophile species in different spatio-temporal arrangements of the annual and perennial elements (Nair 1993), that provide benefits to both wildlife and local people (Montagnini et al. 2015).

Given the climatic restrictions imposed by TDFs (long dry seasons), the main types of AFSs usually performed in this ecosystem are: (i) intercropping systems; consist of agricultural scattered or aligned trees of one or few species, which usually are maintained at a density that does not interfere with crop development (ii) multistrata systems; are typically composed of woody and herbaceous species in diverse configurations and, (iii) silvopasture and protective systems; the first are a generic name for pasturelands with perennial elements, whereas the latter constitute a single or double line of woody elements bordering houses, agricultural plots, or paddocks (Nair 1985, 1989, 1993) (see an extended definition in Table S1).

Some reviews on the benefits of those AFSs indicate that they contribute to people welfare through timber and non-timber products, however, they are typically focus on local or regional analyses rather than more holistic or wide-scale benefits (Roy 2016; Rathore et al. 2019) or are limited to few ecosystem services (e.g., mitigation of climate change, Mbow et al. 2014). Moreover, these studies raise the idea that AFSs in TDFs always generate positive contributions, but this may not be the case in all situations (Sinare and Gordon 2015). Therefore, to improve their efficiency, both the positive and negative contributions of AFSs need to be explored more deeply while also recognizing the relative contribution of different types of AFSs.

Thus, this study analyzes the role of AFSs in providing ecosystem services in TDFs. We adopted the term *ecosystem services* because it has a long tradition of use in research and has been reported in several publications (Braat 2018). We combined a literature review with a *weight of evidence* (WOE) approach (EFSA 2017), a useful semi-quantitative analysis, to organize the information in *lines of evidence* for each ecosystem service (soil quality, production increases, carbon sequestration, biodiversity conservation, and cultural importance). With this approach, we tested the hypothesis that AFSs can restore the provision of ecosystem services in TDFs. Evidence supporting the hypothesis was classified as “benefits” (positive contributions), whereas evidence rejecting the hypothesis was identified as “disservices” (negative contributions or drawbacks). When a study did not provide enough information to sustain the hypothesis, it was classified as “lack of evidence”.

The present study may help researchers and conservation practitioners to recognize opportunities to tailor AFSs in TDFs to enhance the provision of benefits to people, and take actions to tackle local or global environmental challenges (Blackie et al. 2014).

Methods

Literature process selection

The literature survey was performed in the ISI Web of Knowledge Database (Thomson Reuters, New York, USA) on March 2nd 2019, included the search terms [“dry forest” or “dryland*” and “agroforestry” or “agroforestry system*”], which could be in the title, abstract and/or keywords. We also reviewed the “Red SAM” (a thematic network of agroforestry systems in Mexico, http://www.red-sam.org) repository on May 6th 2019, for articles containing the same terms in Spanish [“bosque seco” or “bosque tropical seco” and “agroforestería” or “sistema* agroforestal*”]. We conducted a direct search on two selected publications on the topic: Nair et al. (2017) and Félix et al. (2018). Thus, the identification phase resulted in a total

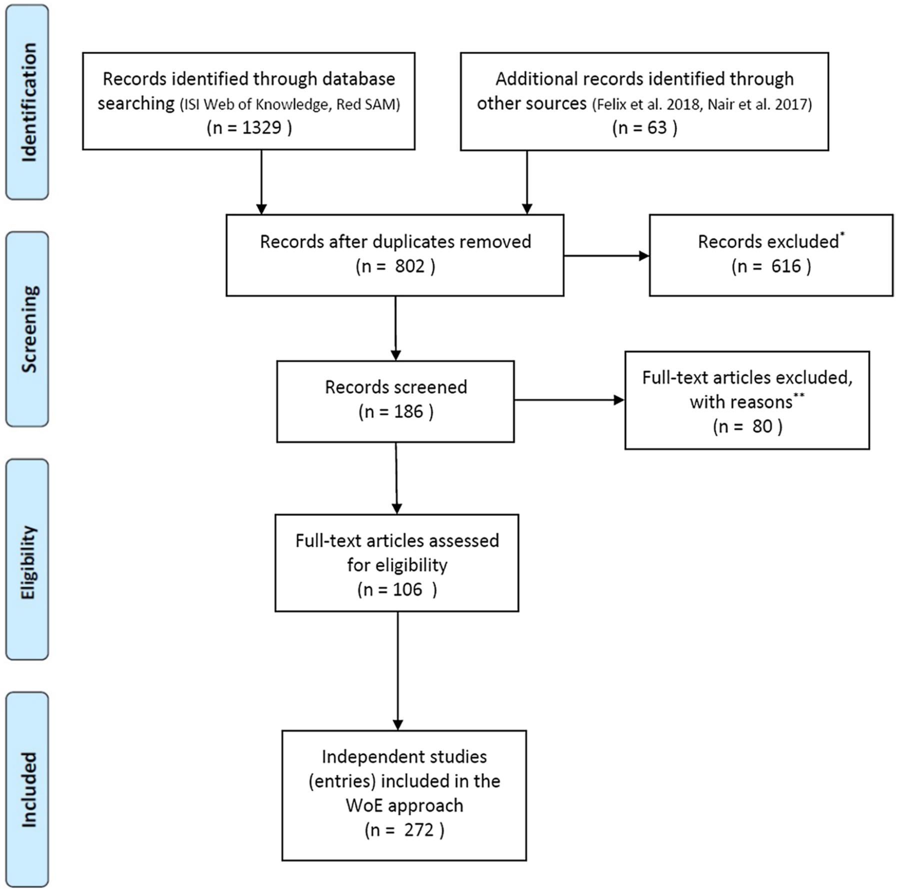

Fig. 1 PRISMA Diagram with the steps of the literature selection process. ISI Web of Knowledge and Red SAM were consulted. Screening phase: * First criterion of selection, the study mentions superficially the term “agroforestry”. ** Second criterion of selection, the ‘climatic criterion’ stated that dryland is an area previously covered by tropical dry forest biome

of 1392 articles (802 duplicates were removed). The literature selection process is summarized in a PRISMA flow diagram (Fig. 1).

In the first filter of the screening phase, we excluded 616 articles as they employed superficially the terms “agroforestry”/“agroforestry systems”, e.g., as an option of sustainable land use strategy in drylands mentioned at the end of discussion. At the end of the first filter, only 186 studies remained. A second filter was applied to verify that studies were carried out in an area previously covered by TDF. We used the delimitation proposed by The Global Ecological Zoning for the Global Forest Resources Assessment-2000 (2001), which establishes that climate of this biome is characterized by annual rainfall ranging from 500 to 1500 mm, one or two dry seasons ranging from 5 to 8 months and temperatures higher than 18 °C; 80 articles did not pass the climatic criterion.

Finally, 106 research articles were included for the analysis: 60 articles from ISI Web of Knowledge, 17 from Red SAM, four from Nair et al. (2017) and 25 from Félix et al. (2018) fulfilled the climatic requirements (Fig. 1, ‘Eligibility’). As many of the research articles described more than one type of AFSs, we finally included 272 independent studies (entries) (Fig. 1, ‘Included’).

The database included information on AFSs type, annual rainfall (mm), perennial elements and ecosystems services explicitly or implicitly highlighted. When available, data on crop yields, measurements of biodiversity, ecosystem (e.g., C stored), economic (profits) and/or social benefits were also gathered. The country and geographic coordinates of the study were used to plot a map where each study was located.

The weight of evidence (WOE) approach

Due to the narrative nature of most data found during the survey, we assessed the services and disservices provided by AFSs in TDFs with a WOE approach. In this approach, evidence and data are structured in *lines of evidence*, which are sets of information grouped by their similarity to assess a hypothesis. Among the different methods that can be used to analyze and synthesize evidence, the *best professional judgement* was used to integrate multiple lines of evidence and infer conclusions from them (Linkov et al. 2009).

We assessed the hypothesis that AFSs restore ecosystems services in TDFs. To evaluate its validity, we explored the following lines of evidence (i.e., environmental services), based on the Millennium Ecosystem Assessment (2005): (1) soil quality improvement (soil structure maintenance, biological diversity, nutrient cycling, (2) belowground C sequestration; (3) production increase (biomass, crop yield and secondary products); (4) biodiversity and agro-biodiversity conservation, and (5) harboring cultural importance. We acknowledge that some of these functions are interrelated to soil quality, such as C sequestration capacity or production; however, we considered the former as one of the strategies to offset greenhouse gases emissions (Nair et al. 2009a, b; UNFCCC 2020), while production was an indicator of agricultural importance.

To complete the database, every study was reviewed to answer the questions “Does the study support, provide no information, or reject the line of evidence? If so, at which degree?” We assigned the scores + 2, + 1, 0, − 1 or − 2 based on the next qualitative criteria: *strong support* (+ 2), when the study reported statistical support to the hypothesis; *weak support* (+ 1), when the study presented narrative arguments of support; *lack of evidence* (0), when the study did not support nor rejected the evidence; *weak rejection* (− 1), when the study presented narrative arguments rejecting the hypothesis or did not present statistical conclusions; and *strong rejection* (− 2), when the study reported statistical conclusions rejecting the hypothesis.

Data analyses

Although SAFs with different names were found in several studies (e.g. parkland, woodlot, living fences, alley cropping, silvopasture, homegarden, windbreaker, among others), and possibly, some AFS are more related to dry forests that receive the maximum volume of precipitation, and others with the minimum amount, to have a larger number of cases for each ecosystem service, we pool all those structurally or functionally similar AFS. In this sense, we analyzed separately evidence only for four generalized AFSs: intercropping systems, multistrata systems, and silvopasture and protective systems. Then, we counted the total number of times a score was assigned. For example, for production increase in intercropping systems, 76 entries were assigned with “+ 2”, 45 with “+ 1”, 27 with “0”, two with “− 1”, and 70 with “− 2”; $n = 220$ (Table S2). We then converted these counts to percentage to standardize and compare lines of evidence with unequal number of entries for each AFSs. Results were arranged and plotted by line of evidence (Fig. 2).

Results and discussion

The continent with the most studies was Africa (45.55%) and Burkina Faso was the most prominent country (14.44% of studies). America was second (35.55%) and two countries had the highest percentages of studies (Brazil, 16.66% and Mexico, 13.33%). India was the country with the highest percentage of studies (10%) in Asia (15.55%, Fig. 2). In Burkina Faso, all studies found were parklands, AFS that prevails in a large part of this continent, while in Brazil and Mexico a wide variety of AFS were evaluated.

Evidence indicated that each type of AFSs provides different benefits (Fig. 3, dark and light green areas) and some disservices (Fig. 3, dark and light red areas) in TDFs. The main types of AFSs recognized for intercropping systems were alley cropping, multipurpose trees, improved fallows, and parklands. For multistrata systems were homegardens and crops under shade. Silvopasture included protein banks and grazing under trees, whilst protective systems comprised living fences and windbreaks. Moreover, the WOE approach allowed us to identify areas of

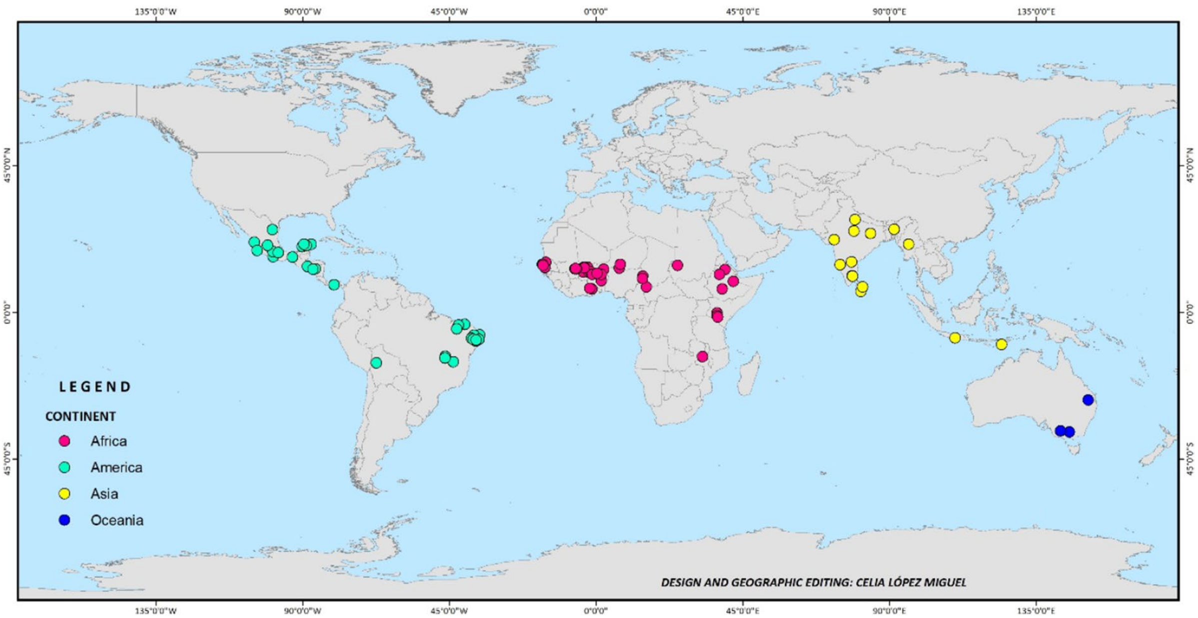

Fig. 2 World map with geographic coordinates of all studies used in the WOE approach

knowledge which have been underexplored (Fig. 3, grey areas). Percentages of evidence supporting and rejecting the hypothesis, the percentage of lack of evidence and number of entries in each case are summarized in Supplementary Table S2.

Benefits

Soil quality

We found evidence that AFSs improve soil quality, but such improvement varies among the types of AFSs. Intercropping systems showed the greatest benefit (total support = 81%, Fig. 3A), with studies reporting increases in soil nutrient stock and soil organic matter (Ceccon et al. 2015; Sileshi 2016) relatively high soil water levels (Ong et al. 2007; Beranger et al. 2017), and reduced soil erosion (van Hoogesteger et al. 2017). Although there was not so much strong evidence for soil improvement in multistrata systems (total support = 54%, 12% strong; Fig. 3A), we found evidence that homegardens do have desirable soil characteristics. For instance, in the Yucatan Peninsula, Mexico, soils in *solares* (traditional homegardens) showed favorable physicochemical characteristics (e.g. relatively high soil organic matter content, neutral to moderately basic pH and heat dissipation capacity) (Flores-Delgadillo et al. 2011) compared to soils in the rest of the peninsula, which are poorly developed (Bautista et al. 2005). The weakest benefit was given to silvopasture and protective systems (total support = 50%, Fig. 3A), although we found some important exceptions. Some silvopastoral systems in Brazil can maintain similar or higher values of soil organic matter than in conventional pastures and native vegetation (Cardozo et al. 2016). Regarding protective systems, in Africa, India and Australia, windbreaks avoid the loss of soil by trapping dust or reducing wind speed (e.g. 5 to 41 t ha^{-1} of soil or 40–200 cm of sand accumulation; Bird et al. 1992; Stigter et al. 2002, respectively). Therefore, some AFSs are better than others in improving soil quality.

Soil improvement is promoted by treed elements in productive lands, so the management of such trees may explain the observed differences among types of AFSs in improving soil quality. Management strategies practiced systematically in some types of AFSs would enhance some of these benefits.

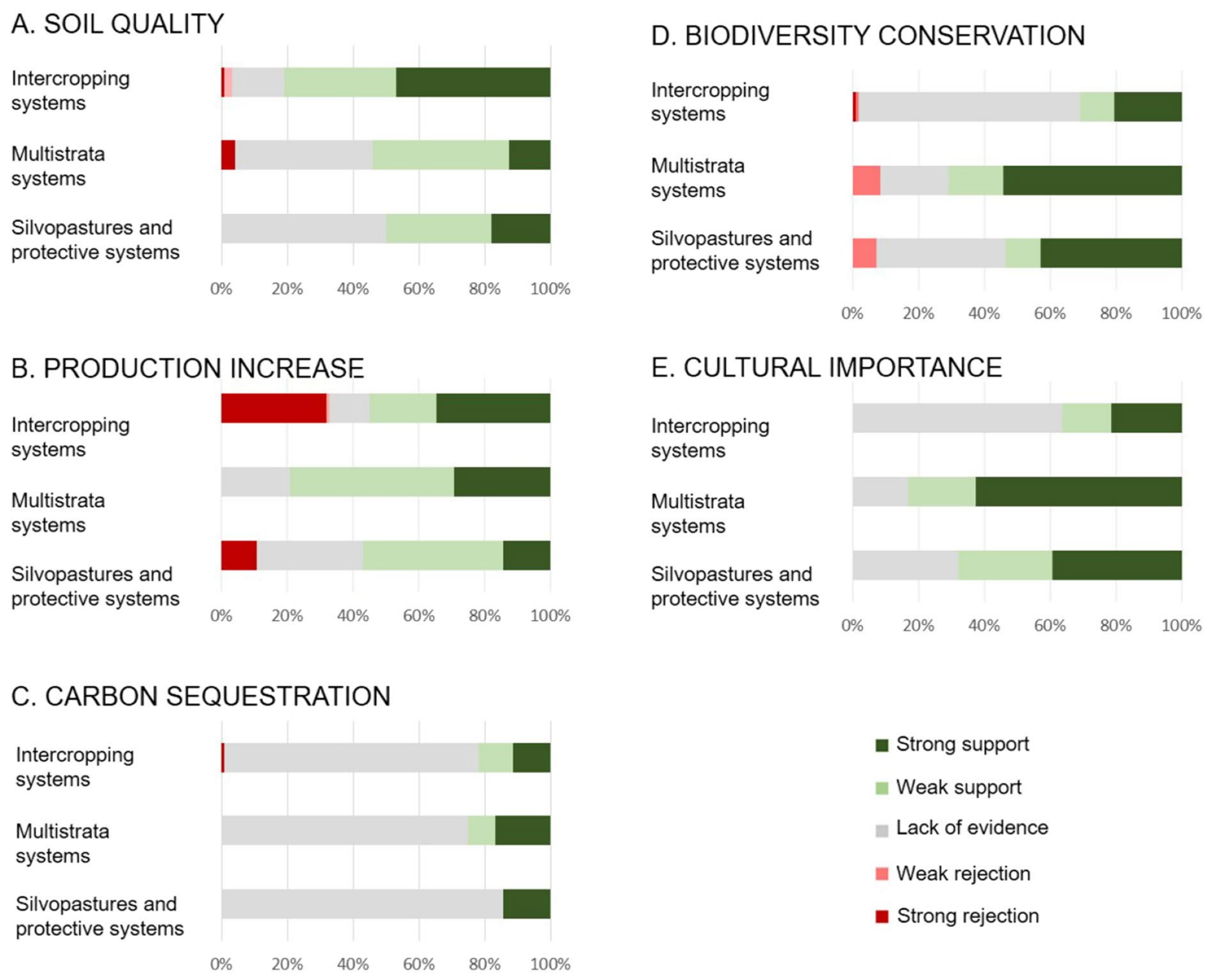

Fig. 3 Weight of evidence for the hypothesis that agroforestry systems can restore the provision of ecosystem goods and services in tropical dry forests. "Strong support" means that statistical conclusions support the hypothesis. "Weak support" indicates that narrative arguments support the hypothesis. "Lack of evidence" encompasses studies which do not support nor reject the hypothesis. "Weak rejection" indicates that narrative arguments reject the hypothesis. "Strong rejection" means that statistical conclusions reject the hypothesis. Number of entries per subsystem (n): intercropping systems, $n=220$; multistrata systems, $n=24$; silvopasture and protective systems, $n=28$. 'n' is the same for all environmental services (See also Table S2)

Production increases

We found considerable evidence that AFSs can increase total production compared with conventional farming systems. By total production we refer to the yield of main staple food crops, the biomass for forage or secondary products (e.g., benefits including food complements, medicines, fuelwood, fodder, or ornaments). Multistrata systems had the highest percentage of support for increased production (total support = 79%, Fig. 3B), especially of secondary products obtained in homegardens. Some of the most cited and highly valued secondary products are fruits, herbs for seasoning, medicine, materials for construction, fibers, fuelwood, and aesthetic/religious/magic plant-based ornaments (Poot-Pool et al. 2012; Larios et al. 2013). This high productivity is mainly since most of the species found in traditional homegardens usually used to be shade tolerant (De Clerck and Negreros-*Castillo* 2000; Martin et al. 2019). Main evidence of production increases for intercropping systems (total support = 54%, Fig. 3B) was obtained for main crops. For example, we find an increase in production of up to of 150% for maize (*Zea mays*, Sileshi 2016), and 274% for taro (*Colocasia esculenta*, Pouliot et al. 2012) compared to their respective monocultures. Similar benefits were found in the yield of silvopasture and protective systems (total support = 54%, Fig. 3B) in which both, woody and grass species, produced more biomass. For example, a Brazilian silvopastoral system can produce more biomass with *Panicum* spp. grass than with *Brachiaria* spp. or grass monocultures (Cardozo et al. 2016). Also, trees employed as living fences in Panama are appreciated for providing secondary products such as fruits, wood, and fuelwood (Garen et al. 2011). Therefore, our findings support the hypothesis that AFSs have the capacity to increase production expressed as crop yields, forage biomass or the provision of secondary products.

An increase in production can be explained by the fact that, when properly designed and managed, AFSs are structurally and functionally complex systems, which may resemble a natural ecosystem and can be highly productive and profitable (Nair et al. 2009a, b; Jose et al. 2019).

Carbon sequestration

Although weakly supported, AFSs also contributed to carbon sequestration. This was more evident in multistrata systems (total support = 25%, Fig. 3C), particularly from homegardens. For example, in Sri Lanka, homegardens from dry and wet zones store, in average, 35 and 87 Mg C ha^{-1}, respectively in above-ground biomass (Mattsson et al. 2013). Intercropping systems (total support = 21%, 11% strong + 10% weak; Fig. 3C) also may contribute to carbon sequestration, although this contribution seems to depend on tree species-soil type interactions. For example, soils under *Acacia auriculiformis* and *Azadirachta indica* growing in a fallow with a Ferric Acrisol soil type in Togo, stored 3.41 and 12.46 Mg soil C ha^{-1} respectively; whereas the carbon stored under *Crotalaria grahamiana* ranged from 1.69, in Arenosol, to 3.6 Mg soil C ha^{-1}, in Ferralsol, in Kenya (Albrecht and Kandji 2003; Partey et al. 2017). Finally, silvopasture presented low support (14% strong; Fig. 3C) but in a Brazilian silvopasture with *Mimosa* spp., *Thiloa glauca* and different grasses stored more C soil (32.8 Mg C ha^{-1}) when compared with a conventional grassland (20.7 Mg C ha-1) (Cardozo et al. 2016). Therefore, the available evidence supporting the value of AFSs in delivering this environmental system service is not so strong, however, its importance is not negligible considering that natural forested areas are rapidly decreasing.

Biodiversity conservation

Our findings also support the hypothesis that AFSs provide niches for a wide range of plant and animal species, above and below ground. The strongest evidence comes from multistrata systems (total support = 71%, Fig. 3D), especially from homegardens, within which 50 to 70% of trees are composed of native species and the herbal stratum includes native and introduced species or varieties (Moreno-Calles et al. 2016; Aguirre-Salcedo and Ceccon 2020 among others). Silvopasture and protective systems also promote biodiversity (total support = 54%, Fig. 3D). For example, in a Mexican silvopastoral landscape, the species richness of Scarabaeinae beetles increased from highly managed patches (rangelands with no trees) to intermediate- or low-managed ones (*Acacia* spp woodlots and mature TDF) (Arellano et al. 2013). Regarding protective systems, in Panama, nearly 90% of the tree species employed as living fences are native to this country (Garen et al. 2011), and in central Mexico, up to 61 species of birds coexist in living fences in agro-silvopastoral landscapes (Zuria and Gates 2013). Finally, biodiversity conservation was relatively less evident in intercropping systems (total support = 31%, Fig. 3D). Yet, some exceptions merit special attention: in the Tehuacán Valley, Mexico, *jiotillales, chichiperas* and *garambullales,* complex traditional systems, involving multipurpose trees in croplands and cacti as living fences, preserve nearly 94% of genetic variation of columnar cacti species (Moreno-Calles and Casas 2010), which is of major importance given that the area is center of diversification and endemism for Cactaceae family (Dávila et al. 2002). Therefore, we confirm our hypothesis that AFSs conserve wild and domesticated plants and animals, according to the type of system.

The capacity of AFSs to harbor biodiversity and agrobiodiversity seems to be related to their complex structure, which in turn is driven by management strategies. Farmers introduce, conserve or tolerate diverse perennial and annual species in their AFSs (the ´planned biodiversity´, Altieri 1999), and manage them to maximize positive interactions – traduced in profits—and minimize competition – traduced in drawbacks (Nair et al. 2009a, b). Some species from the surrounding ecosystems benefit on the environmental setting created by the AFSs and can play beneficial (e.g., pollination or suppression of 'undesirable' organisms) or negative roles (e.g., feeding on main crops or compete with them, Hellin et al. 1999). AFSs also improve the human modified landscapes facilitating ecological processes, such as pollination, seed dispersal or genetic connectivity among forest fragments (Arroyo-Rodríguez et al. 2020).

Cultural importance

Evidence indicates that AFSs are of cultural importance, which refers to the values and meanings that people give to the positive contributions generated in AFSs, such as food, medicine, fuelwood, fodder, material for construction, ornaments, and the monetary income (Millennium Ecosystems Assessment 2005).

Evidence on cultural importance was noticeable in multistrata systems (total support = 83%, Fig. 3E), especially in homegardens, where the production usually covering part of daily-life household demands in rural or poor communities (Poot-Pool et al. 2012; Larios et al. 2013 among others). Evidence for cultural importance for silvopasture was also high (total support = 68%, Fig. 3E), and the most representative evidence was found on protective systems (Garen et al. 2011). In Burkina Faso, livestock wander freely during the dry season and sometimes, animals go inside private backyards and cause damages to the neighbor's property. Woody poles or barbed wire are expensive or scarce, so farmers employ living fences as the most profitable option to keep cattle out of their properties and because of the secondary products they obtain (Ayuk 1997). Cultural importance was less evident in intercropping systems (total support = 36%, Fig. 3E). In African parklands *Vitellaria paradoxa* (shea nut or *karité*) trees are part of the Sahelian landscape, and its fruits are one of the main sources of energy for peasants during the hardest season of land preparation; moreover, fruit collection, butter extraction and trading –activities carried out mainly by women- generate important economic revenues (Maranz et al. 2004). Therefore, our findings support the hypothesis that AFSs are of cultural importance because of the material and immaterial positive contributions generated there.

Disservices

Some evidence in this study show that AFSs may also deliver disservices or negative contributions (Fig. 3, dark and light red areas). We considered disservices as tradeoffs between positive contributions and decreased performance in other ecosystem functions. However, almost all the impacts presented low percentage of rejection (< 3%). The only moderate rejection found was the impact on the yield in intercropping systems (total rejection = 33%, Fig. 3B), where yield reductions ranged from -3% to -81% (de Ruijter et al. 2010 and Glasener and Palm 1995, respectively). Although water or nutrient competition may explain the negative results on crop yields (Nair 1993; García-Barrios and Ong 2004; Ong et al. 2007), sun light complex interactions seem to be also involved. Studies on crop performance under tree crowns vs open areas are suggest.

Knowledge gaps

Carbon sequestration capacity was the greatest knowledge gap for all types of AFSs. We found high percentages of lack of evidence in silvopasture and protective systems (86%), intercropping systems (77%) and multistrata systems (75%, Fig. 3C). Moreover, biomass addition to soil sometimes results in greenhouse gases emission, and it is not clear under which circumstances this phenomenon is triggered (i.e., soil type, fixing- or non-N-fixing species, management practices). To overcome this gap, gathering data on characteristics of the system, such as the tree litter quality, management practices, soil characteristics and agroclimatic conditions, can serve to model the C storage capacity of different AFSs and improve our understanding about their performance across different contexts (Nair et al. 2009a, b). Filling this research gap may also provide information to establish threshold quantities of biomass application or to develop strategies to limit greenhouse gases emissions (Glasener and Palm 1995; de Ruijter et al. 2010).

Conclusions

We provided a nuanced understanding of the different degrees of evidence for the contribution of AFSs to maintaining or restoring the provision of goods and ecosystem services ("positive contributions" or benefits). Yet, disservices ("negative contributions" or drawbacks) were also documented. We also found a close relationship between management practices and the capacity of AFSs to provide positive contributions. Thus, farmers usually obtained more benefits when an AFSs was more intensively managed, that is, more organic inputs added, higher number of species sheltered or more intensively labored. To scale-up the adoption of AFSs as an instrument for productive restoration, however, the involvement of the private and public sector as well as academics and local groups it is needed.

Finally, as a methodological consideration, the WOE approach proved to be a useful framework to conduct semi-quantitative reviews of the ecological literature. This approach allowed us to frame and assess information on ecosystem services (i.e., lines of evidence) coming from different fields of knowledge. It was also especially useful with narrative-type literature (e.g., ethno-ecology, botanical or zoological list), in which statistical conclusions are not always available. Furthermore, the WOE allows to test diverse lines of evidence in the same analysis (five in the present study).

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