

## Article

# Ecosystem Services from Ecological Agroforestry in Brazil: A Systematic Map of Scientific Evidence

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**Abstract:** (1) Brazil has great potential to expand the area under agroforestry, and thereby simultaneously enhance multiple ecosystem services. However, divergent interests are currently polarized between drastic environmental deregulation and public resource allocation to chemical-intensive land use versus conservation and sustainable agriculture. This highlights an urgent need for a comprehensive overview of the evidence of the benefits to society generated by agroforestry across Brazil. (2) We present a systematic map of the scientific evidence related to the effects of agroforestry on ecosystem services in Brazil. (3) Reviewing 158 peer-reviewed articles, published in international scientific journals (database: Web of Science), we identified a disproportionate emphasis on the Atlantic Forest. Very little research has been published on the Cerrado savanna, Pampa grasslands and Pantanal wetlands. Regulating services were much more frequently studied (85%) than provisioning (13%), while cultural services represent a major gap. A consistent positive effect of agroforestry was demonstrated for soil quality, habitat and food provisioning. Trade-offs were demonstrated for soils and habitats. (4) Our analysis identifies high-priority gaps given their critical importance for human well-being which should be filled: agroforestry effects on water provision and regulation. Moreover, they should assess other ES such as erosion control, flood protection and pest control to enable a more reliable inference about trade-offs.

**Keywords:** agroforests; Nature's Contributions to People; agroecology; ecological intensification; land-sharing



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## 1. Introduction

The extensive implementation of industrial agriculture has been heavily impacting several ecological processes that sustain human well-being—ecosystem services (ES) [1,2]. The intensive application of pesticides and fertilizers and the genetic uniformity in these systems has led to pest resistance [3,4], biodiversity loss [5–7], soil degradation [8], greenhouse gas (GHG) emissions [9] and contamination of food and water with agrochemicals [10,11]. These environmental and socioeconomic costs associated with increases in productivity of single commodities in industrial monocultures represent a prioritization of provisioning services at the expense of enduring losses in regulating services, such as pollination, carbon sequestration, biological control and soil conservation, posing a strong trade-off among ES [1,12–14].

A growing number of scientific papers have been focusing on diversified farming systems and their potential to generate multiple ecosystem services that can drastically reduce the dependence on market inputs, as well as to attenuate some of their negative impacts [15–18]. For instance, agroforestry has been proposed to generate a portfolio of

regulating ES [19,20], including C sequestration [21,22], on-farm habitat provision [23,24]; regulation of water flows and water quality [25]; enhancement of soil productive potential [19,26]; pest, disease and weed regulation [27], among many others. Agroforestry may enhance the mean and diversity of these regulating services while maintaining and diversifying provisioning services through the production of forest resources including food, timber and medicinal products [20,28].

Some literature reviews related to the topic were performed at the national [24,29], regional [30–32] and global scale [33,34]. However, most of them have focused on one or just a few ecosystem services [21,27,35–40], or on one specific agroforestry practice, such as alley cropping systems [41], cacao agroforestry [34,42,43], or coffee agroforestry [44–47].

Although some reviews are available, for most of them the limited scale, context specific characteristics and type of systems investigated hinder the possibility of generalizations. The few systematic reviews and meta-analyses that cover this broad topic were performed very recently and especially at the European scale [48–50]. In South America, a recent meta-analysis has been performed for the Brazilian Atlantic Forest [21].

In Brazil, the intensive application of industrial agriculture has placed the country among the world's largest users of agrochemicals [51,52] and is responsible for a high deforestation rate [53,54]. Brazil also harbors significant amounts of the world's freshwater [55], forest biodiversity [56–58] and cultural diversity [59], generating important ecosystem services for society. As a primarily tropical and forested country with an outstanding sociocultural and educational basis, Brazil has a great potential to scale out and scale up the implementation of agroforestry.

Agroforestry encompasses a wide range of land-use systems where woody perennials are deliberately grown on the same land unit as other agricultural crops or animals for their intentional, multifunctional interactions among components [60]. In Brazil, some programs and initiatives promote the implementation of agroforestry with the same management practices of the industrial monocultures, which are also referred to as agronomic or conventional agroforestry [61]. However, there is rapidly growing farm implementation in Brazil and beyond of agroforestry systems that intend to mimic and accelerate key processes of forest succession and that are oriented by agroecological principles such as the reduced dependence on external inputs, integrated management to enhance ES, such as biological control and nutrient cycling, water and soil conservation, among many others [62–64].

Compared to the 263 million hectares under farming systems (2020), which represents approximately 30% of the national territory, agroforestry in Brazil covers around 5% of the farmed land, and there is no information if these agroforests follow the conventional model or are oriented by agroecological principles [65]. There has been an increasing recognition of the potential of agroforestry to restore and maintain more sustainable and productive landscapes across the vast tropical country, especially for smallholding agriculture [66,67]. Apart from the growing body of literature that has been published [68] and the efforts of some independent initiatives currently taking place in Brazil [69–71], this mounting recognition is also demonstrated by the recent changes in some of the national legislation that regulates land for agricultural purposes. Agroforestry can now be used to restore and maintain the legally protected areas within small rural properties [72]. Moreover, agroforestry is being recommended as an alternative for the restoration of 12 million hectares of degraded pasture in Brazil under the National Plan for the Recovery of Native Vegetation [73].

So far, it is unclear whether or not there is enough evidence available to support decision-making processes related to agroforestry and ecosystem services in Brazil. In general, the scientific evidence is scattered and fragmented in primary studies that tend to investigate limited interventions in specific contexts. This fragmentation hinders the possibility to draw on broad conclusions that can support efficient decisions. Science has to take the responsibility of communicating the results to decision/policymakers, in a way they can understand. Up to now, some literature reviews on agroforestry were

performed in Brazil, but mainly on more specific topics and not following a systematic guideline [42,66,74–76].

Therefore, the current review seeks to fill this gap by producing the first systematic map to catalog the available scientific evidence related to the effects of ecological agroforestry on ecosystem services in Brazil, aiming to better grasp the research trends and identify the main knowledge gaps. Thus, it is possible to set a research agenda with priorities that can result in more efficient use of the scarce public research investments and further develop a body of evidence that can support decision-making processes. To this end, we addressed specific questions: What evidence has been published on ecosystem services generated by agroforestry oriented by agroecological principles in Brazil? Did the studies adequately cover Brazilian regions and biomes? Which ecosystem services are more positively or negatively affected by agroforestry? What are research gaps of high priority on the topic?

## 2. Materials and Methods

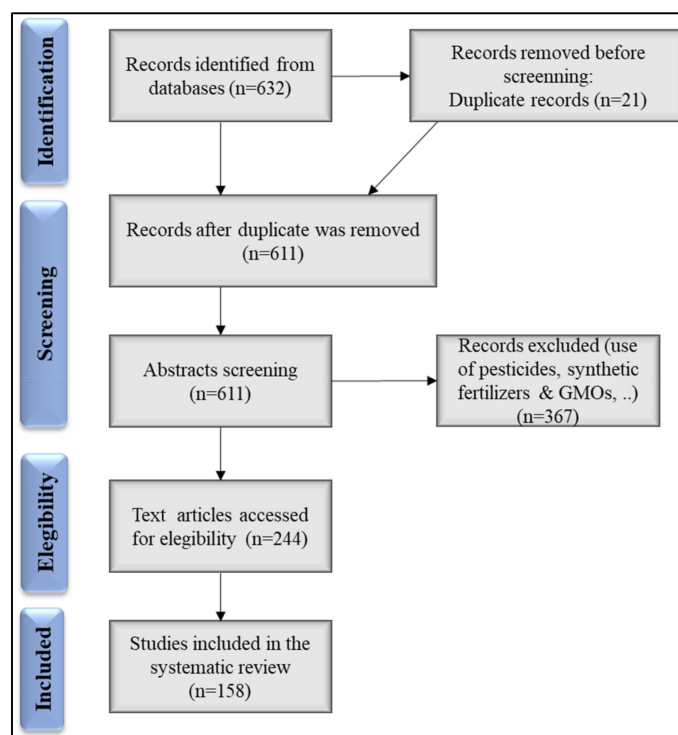
For the review of journal articles about ecological agroforestry in Brazil and its effects on ES we followed guidelines for systematic review and systematic mapping [77,78]. Both evidence-synthesis methods follow similar rigorous, transparent and objective steps with the aim to reduce bias. However, while the systematic review is used to answer a specific and “closed-framed” question, often requiring a precise set of primary research, systematic mapping is recommended for those “open-framed” questions. The main goal is to collate and catalog all available evidence on a broad topic to understand how much research has been conducted on it, to identify and gather important evidence for policy-relevant questions and to detect evidence gaps [78,79].

The search for peer-reviewed journal articles was carried out on the Web of Science database, using the generic terms: “Agroforest\*” (topic) AND “Bra?il” (topic). Therefore, for the systematic mapping, we considered only those articles evaluating agroforestry that met the following criteria: (1) systems that deliberately and functionally integrate crop mixtures with at least one woody perennial species and another woody or crop or forage species; (2) secondary forest enrichment with economically used species (as long as forest structure was maintained) and (3) extractive forest management (as long as forest structure was maintained). We excluded conventional agroforestry systems that (1) applied pesticides, (2) highly soluble synthetic fertilizers, or (3) used genetically modified organisms (GMOs).

Even though we are aware that agroecology cannot possibly be limited to the reduction or substitution of external inputs [80], our review is limited to this aspect of the agroecological spectrum since a large portion of published articles did not provide sufficient information to assess whether or not a range of agroecological principles were used in the agroforestry systems reported. We understand that systems that reduce or substitute the use of industrialized inputs are one step forward towards more sustainable agriculture, representing a significant step in the agroecological transition [62].

The journal articles resulting from the search were refined through a two-step screening process: (1) the title and the abstracts and (2) the methodology, results and conclusions. During this process, we verified if the publication fulfilled the inclusion criteria and demonstrated clear evidence of agroforestry positively or negatively affecting the generation of ES. For this study, we considered as evidence the effects demonstrated as results of the scientific method utilized in the specific primary research. Nevertheless, evidence was interpreted according to the ecosystem service(s) affected, which we then called ‘items of evidence’. Therefore, evidence resulting from primary research could be interpreted as one item of evidence (if it only addresses effects on one type of ES), or more items, for those that can represent a direct effect on more than one ecosystem service type.

The Web of Science search (October 2021) yielded 632 journal articles, with the oldest one being from 1982. After the filtering stage, the 632 results were narrowed to 158 articles that reported agroforestry (AF) effects on ES, resulting in a total of 216 items of evidence related to the ES we classified (Figure 1). Metadata of all original studies that met the inclusion criteria is available in File S2.



**Figure 1.** Diagram flow showing the research steps for article selection.

After the filtering stage, the evidence interpreted from each journal article was classified according to the Common International Classification of Ecosystem Services (CICES) V5.1 [81]. CICES is a classification that was developed by the European Environment Agency (EEA) and has been used mainly for mapping and assessments of ecosystem services [81]. For detailed CICES classification of our ecosystem service terminology, see File S1.

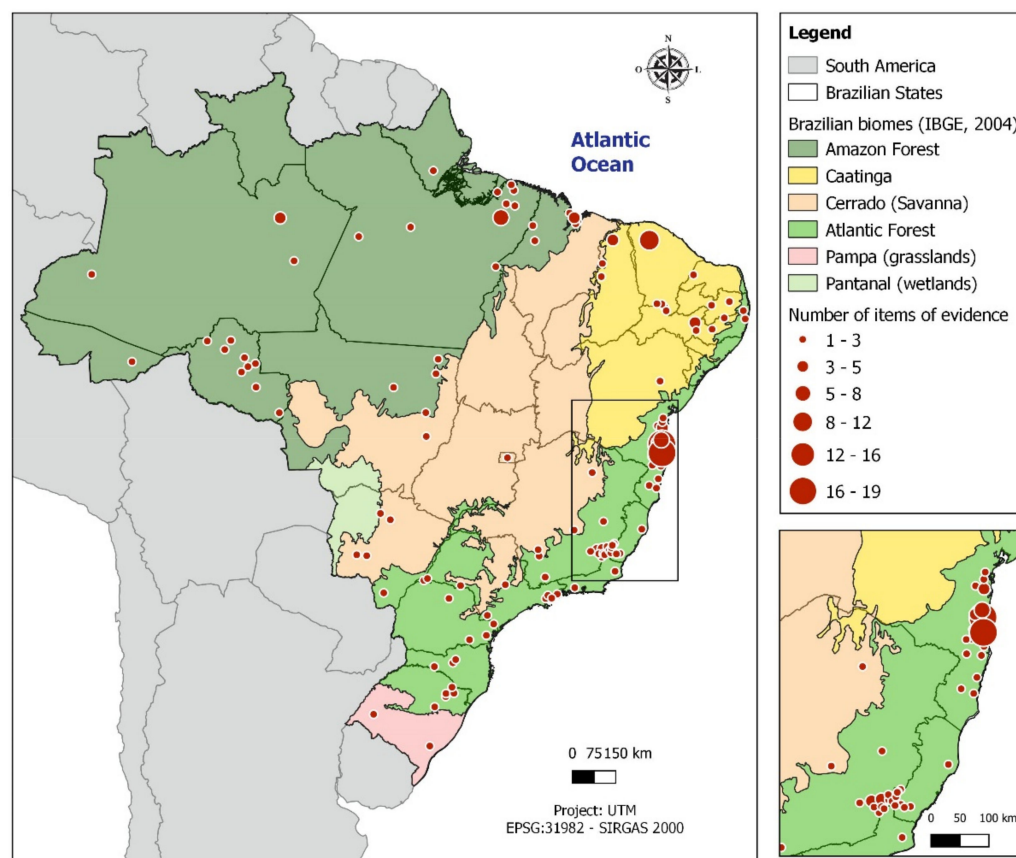
All included references were entered into a spreadsheet, which included bibliographical information (author, year, DOI and title of the article), ES class (cultivated plants grown for nutrition; fibers and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing; regulation of the chemical composition of the atmosphere and oceans; control of erosion rates; decomposition and fixing processes and their effect on soil quality; weathering processes and their effect on soil quality; hydrological cycle and water flow regulation—including flood control; maintaining nursery populations and habitats—including gene pool protection; pest and disease control; regulation of temperature and humidity—including ventilation and transpiration); AF type (agrosilvicultural, silvopastoral, agrosilvopastoral) and methodological approach (observational, experimental or modeling). We also recorded the administrative and biogeographical location of the AF systems studied (municipality, state, region and biome). This data was used to produce a map in QGIS version 3.4.14 software, basically composed of overlapping layers of the six Brazilian biomes and the municipalities where each of the studies was conducted. The three types of agroforestry systems were grouped and characterized according to the predominant land use type, spatial arrangement, composition and dominant crop species. Full bibliographic and geographical metadata of all studies included in this systematic mapping and summarized effects documented, AF types, methodological approaches and ES classes are provided in File S2.

### 3. Results

#### 3.1. Biogeographical Distribution of Evidence and Types of Agroforestry Systems

The 158 studies were performed in 135 different municipalities in five out of the six Brazilian biomes (Figure 2). Almost half of the studies (49%) were performed in areas

pertaining to the Atlantic Forest biome, which retains less than 15% of its original area under primary and secondary forests [65]. The Amazon has the greatest extent among the Brazilian biomes and approximately 80% of its original vegetation cover, where 23% of the studies were performed on. The Brazilian Savanna (Cerrado) represents the second largest and second-most disturbed Brazilian biome after the Atlantic Forest, with less than 40% of its original vegetation remaining [65]. Yet only 7% of the analyzed studies were from the Cerrado. However, some studies (2%) were performed on transitioning areas between Cerrado and Atlantic Forest biomes. Caatinga, the semiarid thorn scrub biome in Northeastern Brazil, has a substantial share of the studies (18%) considering its smaller area (less than 10% of Brazil's territory and 60% of its natural vegetation remaining). Of the six Brazilian biomes, two had almost no representation among the studies reviewed. In the Pantanal, which represents one of the largest wetland areas of the world [82] and retains a large portion of its natural vegetation (83%), no studies analyzed agroforestry [65]. A single study was performed on the Pampa, a grassland biome restricted in Brazil to its southernmost state, with around 50% of natural vegetation [65].



**Figure 2.** Map of Brazilian biomes and geographical distribution of the agroforestry sites studied in the 158 journal articles. Box on the right highlights the area with the highest concentration of studies assessed in Southeast Bahia State.

Some specific regions on the map (Figure 2) are characterized by a strong overlap of studies, represented by larger and intersecting circles. Most of these sites are located within the Northeast region of Brazil, where 46% of the studies were conducted. Among these thoroughly studied regions, the southern part of Bahia state represents a considerable portion of all studies reviewed, with more than 30 different articles focusing on this area. This is because the region holds large land areas that are used for cacao (*Theobroma cacao*) production under the shade of native or exotic trees, which characterizes the traditional agroforestry systems known as *cabruca* [74].



The *cabruca* landscape mosaic is the most studied type of agroforest in Brazil. For a long time, the region has been a target for research, and the number of publications keeps growing. Most studies assessed the potential of these systems to reconcile production and biodiversity conservation [83–85].

In our review, agrosilviculture was the most common type of ecological agroforestry, being present in 86% of the papers reviewed. Similar to the *cabruças*, we found agroforests focused on coffee (*Coffea arabica*), yerba mate (*Ilex paraguariensis*) and fava d’anta (*Dimorphandra gardneriana*) production below secondary forest remnants with different degrees of canopy cover in the Atlantic Forest, Cerrado and the Amazon. Sisal fiber (*Agave sisalana*) production within the Caatinga vegetation was more common in the Northeast region of Brazil (Table 1).

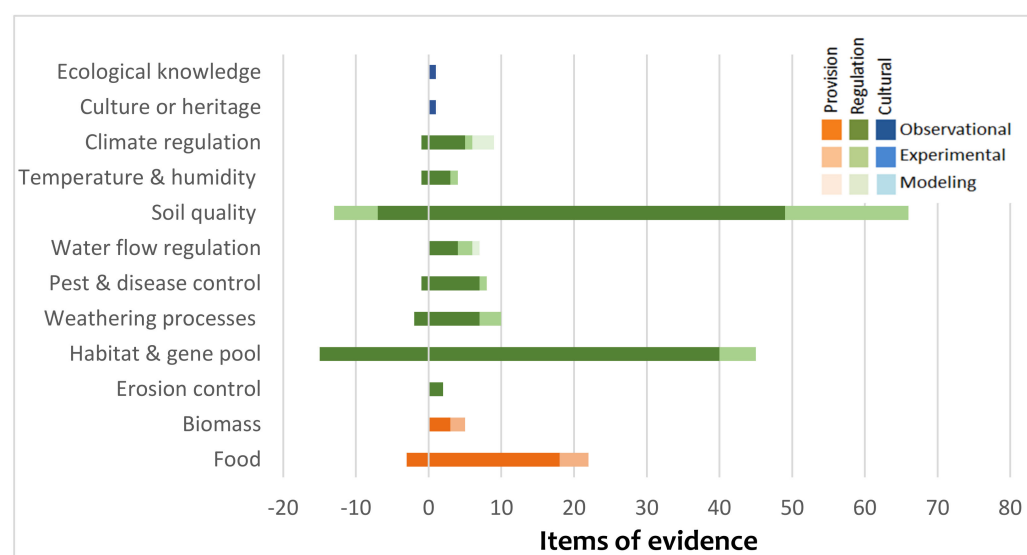
**Table 1.** Examples of agroforestry types assessed in the literature.

| Types of AF        | Predominant Land Use       | Spatial Arrangement | Composition                                                            | Dominant Crop Species                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|--------------------|----------------------------|---------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Agro silvicultural | Mainly forest              | Mixed dense         | Secondary forest + perennial crop                                      | Cacao ( <i>Theobroma cacao</i> ), coffee ( <i>Coffea</i> sp.), yerba mate ( <i>Ilex paraguariensis</i> ), fava d’anta ( <i>Dimorphandra gardneriana</i> ), rubber tree ( <i>Hevea brasiliensis</i> ), sisal fiber ( <i>Agave sisalana</i> ), oil palm                                                                                                                                                                                                                                                                                                                                   |
|                    | Mainly forest              | Mixed dense         | Perennial crop + tree for shade/biomass/other                          | rubber tree + coffee, cacao + rubber tree, cacao + erythrina ( <i>Erythrina glauca</i> ), coffee + araucaria ( <i>Araucaria angustifolia</i> ).                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|                    | Mainly forest              | Mixed dense         | Perennial crop + mixed trees                                           | Coffee, rubber tree, cacao, etc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|                    | Mainly forest              | Mixed dense         | Mixed trees/shrubs planted for diverse purposes                        | Fruits: papaya ( <i>Carica papaya</i> ), guava ( <i>Psidium guajava</i> ), banana ( <i>Musa</i> sp.), cashew ( <i>Anacardium occidentale</i> ), mango ( <i>Mangifera indica</i> ), palm tree ( <i>Euterpe edulis</i> ), cupuaçu ( <i>Theobroma grandiflorum</i> ), açai palm ( <i>Euterpe oleracea</i> ), andiroba ( <i>Carapa guianensis</i> ), coconut ( <i>Cocos nucifera</i> ), citrus. Biomass or wood: eucalypt ( <i>Eucalyptus</i> sp.), leucena ( <i>Leucaena leucocephala</i> ), native species, manioc ( <i>Manihot esculenta</i> ), pigeonpea ( <i>Cajanus cajan</i> ), etc. |
|                    | Mainly agriculture         | Stripes             | Intercropping of agricultural crops with diverse tree species in alley | Corn ( <i>Zea mays</i> ), rice ( <i>Oriza</i> sp.), sorghum ( <i>Sorghum</i> sp.), cashew, mango ( <i>Mangifera indica</i> ), etc.                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|                    | Mainly agriculture         | Stripes             | Perennial crop + agricultural crops                                    | Coffee and corn/beans, etc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Agro silvopastoral | Mainly pasture/agriculture | Mixed sparse        | Intercropping of agricultural crops + forage + mixed trees             | Coffee, prickly pear ( <i>Opuntia ficus-indica</i> ), manicoba ( <i>Manihot glaziovii</i> ), eucalyptus, acacia ( <i>Acacia mangium</i> ), etc.                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Silvopastoral      | Mainly pasture             | Stripes             | Forage + trees in alleys for biomass/wood                              | Paricá ( <i>Schizolobium amazonicum</i> ), coffee and shade trees, cashew, leucena, glirícidia ( <i>Gliridia sepium</i> ), etc.                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|                    | Mainly pasture             | Mixed sparse        | Forage + sparse native trees                                           | Species from the families Boraginaceae, Fabaceae, Apocynaceae. etc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |

Rubber tree and perennial crops as cacao, coffee and oil palm (*Elaeis guineensis*) were found in intercroops of two species or more, including other native and/or exotic trees planted with different purposes. The combination of diverse species planted together for various purposes (fruits, nuts, oil, forage, etc.) was spread in different regions, but most often in the Cerrado and the Amazon. Silvopastoral systems within the criteria of this study were found in 14% of the papers reviewed. The use of trees in alleys was more common for paricá (*Schizolobium amazonicum*), leucena (*Leucaena leucocephala*) and gliricídia (*Gliricidia sepium*). The combination of pasture with various nuclei or isolated native tree species was normally associated with deforested areas where these species were left behind. The Agrosilvopastoral system was the least common type of agroforestry among the studies reviewed. Coffee (*Coffea arabica*), prickly pear (*Opuntia ficus-indica*), manioc (*Manihot esculenta*), eucalyptus (*Eucalyptus* sp.) and acacia (*Acacia mangium*) were the most frequent species used for biomass, fuelwood, timber and fruit production (Table 1).

### 3.2. Agroforestry Effects on Ecosystem Services

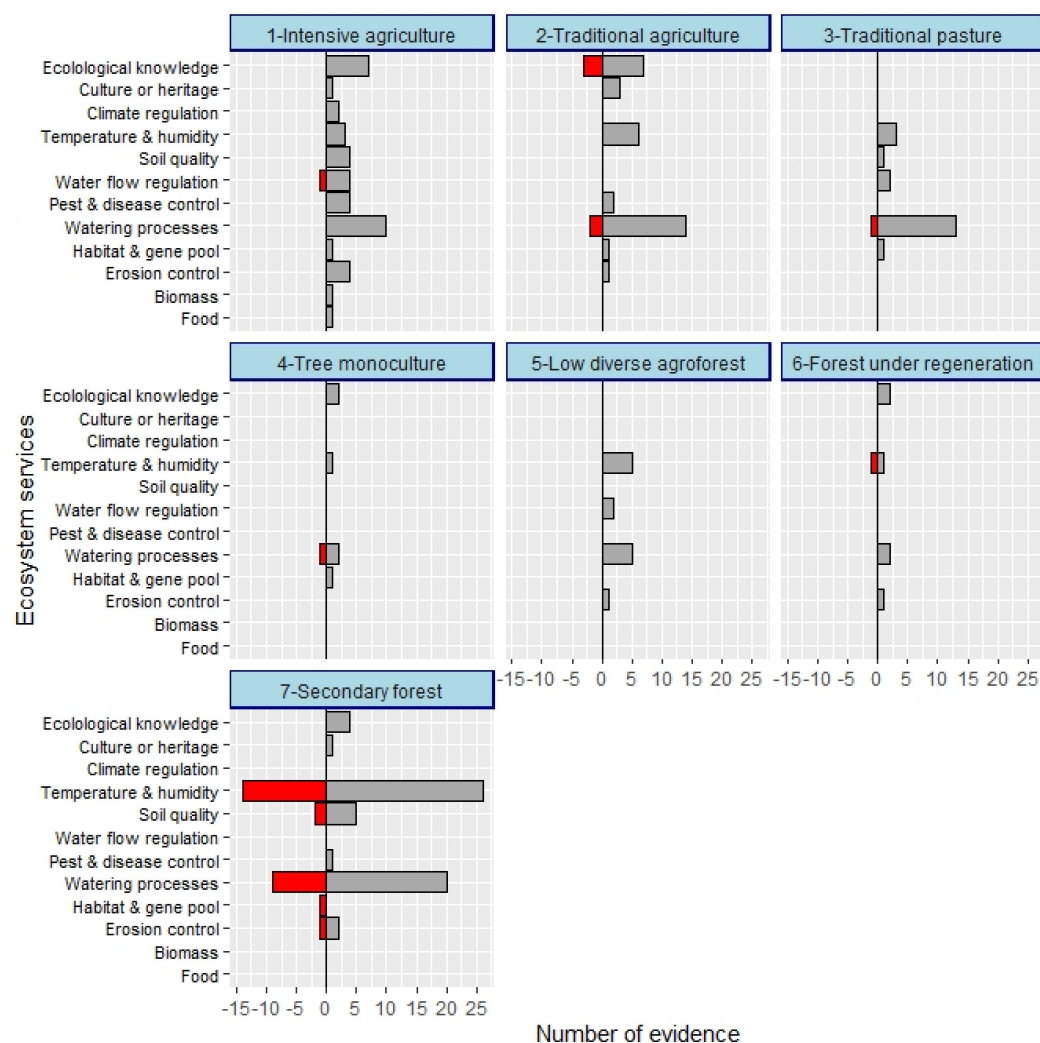
Overall, our systematic mapping yielded 216 items of evidence of ecosystem services, classified according to the Common International Classification of Ecosystem Services [81] (details in File S1). The evidence found in the articles reveals 180 positive effects of agroecological agroforestry on ecosystem services and 36 cases of tradeoffs (Figures 3 and 4; full metadata in File S2).



**Figure 3.** Evidence of positive effects (positive scale) and tradeoffs (negative scale) of agroforestry (AF) on ecosystem services (ES) in Brazil (full metadata in File S2).

The 36 cases of tradeoffs found include 8 tradeoffs measured among different variables negatively affected by AF when compared to different agricultural systems such as slash and burn agriculture, traditional pasture, crop monoculture, tree monoculture and low diversity agroforestry. Of all cases of tradeoffs identified, 28 were considered implicit tradeoffs, where productive AF had inferior performance than undisturbed native vegetation or native forest under restoration (Figure 4).

Most evidence of the reviewed literature was obtained through observational studies (71.5%), while a smaller portion resulted from experimental studies (27%). Modeling studies represented 1.5% of the reviewed evidence. Among the three categories of services, regulating ES was the most studied type, representing 78% of items of evidence. Provisioning ES had 21% of the evidence, while almost no evidence was found for cultural services (less than 1%), with no study singly focusing on this type of ES.



**Figure 4.** Number of items of evidence of positive and negative effects of agroforestry systems on ecosystem services in comparison with seven different land use & land cover types (full metadata in File S2).

Soil quality and habitat & gene pool were the two most studied services. For these two service types, most items of evidence reported positive effects of AF, but also quite a few related to the tradeoffs among ES in these systems when compared to the secondary forest (item 7 Figure 4). Cultivated plants grown for nutritional purposes (food) were the third most studied ES. Climate regulation, pest & disease control and water flow regulation had been documented with similar numbers of items of evidence.

Approximately 40% of the studies used the secondary forest as the main land use land cover (LULC) type as a basis for comparison of ES production with the AF systems. Intensive and traditional agriculture were the second most frequent ones and most of the evidence found showed a positive effect of AF. Intensive agriculture was often represented by large-scale crop monoculture focused on commodities production, while traditional agriculture was related to slash and burn practices conducted in small areas. The “low diversity agroforestry” system was a type of LULC used for comparison with biodiverse AF systems mainly in the region of southeast Bahia, where the level of species diversity and composition of the *cabrucas* AF systems vary significantly. Forest under regeneration and tree monoculture were the LULC types least found in the literature. Silvopastoral systems were used for comparison with traditional pasture and had a mainly positive effect on ES production (Figure 4).



### 3.3. Soil Quality

Among the studies that assessed soil indicators, carbon and nitrogen content were the properties most frequently assessed. Most of these studies found a positive effect of AF on these properties, which are key to determining soil quality. They demonstrated that AF has a comparable and sometimes even greater potential for carbon sequestration and nutrient cycling compared to secondary vegetation, as well as to traditional agriculture and pasture. Some studies attributed these positive effects to the management practices adopted, such as constant incorporation of plant residues from pruning and weeding [86–94], the use of legume trees [86,95–97] and organic fertilization, including inputs of animal manure [88–90].

Another share of these studies inferred that the positive effects of AF on soils were related to species structure and richness. By comparing different types of AF (with a different number of species) and natural vegetation as a control, these studies found better contributions for soil quality from the most diverse and rich AF than from the least diverse and rich ones [87,91,98–101].

Some studies pointed out potential reasons for soil quality tradeoffs. By comparing different types of AF with native vegetation and other land uses, different studies [102–104] concluded that those AF that promoted higher disturbances in the soil caused a reduction in nitrogen contents and total soil organic carbon stocks compared to the native forest and to treatments that had less intensive soil disturbances. This effect is also demonstrated by another study [101] that concluded that those AF with higher floristic diversity registered a high concentration of soil carbon contents and stocks, increasing the quality of the added organic material, and consequently the humification processes that contribute to the long-term storage of carbon.

### 3.4. Habitat & Gene Pool

Among the studies that assessed the potential of AF for biodiversity conservation, a greater proportion evaluated faunal species, including insect communities (hematophagous insects, dipterous, ants, mites and beetles) and mammals (small mammal communities, primates, bats, sloths). Several concluded that AF can be considered as an important strategy for the conservation of various species [28,105–114]. However, others provided evidence of tradeoffs, demonstrating inferior habitat provision for some animals and plant communities in AF compared to secondary vegetation [101,115–120].

Many studies compared the potential for conservation of different animal and plant species among different types of cacao agroforest, such as *cabruca*, rubber agroforest (cacao shaded by rubber trees—*Hevea brasiliensis*) and *Erythrina* agroforestry (cacao shaded by *Erythrina glauca* or *Erythrina fusca*). The majority of these studies concluded that cacao agroforests with a more complex and diverse vegetation structure, being mainly shaded by native trees, were better able to maintain subsamples of the communities found in the adjacent forests than the monodominant agroforests [101,110,121,122]. The presence of large-diameter native trees was also pointed out as an important attribute for habitat use of mammal species in *cabruca*s [113]. As presented by many studies, the potential of *cabruca*s as an alternative or additional habitat for forest species is also dependent on the quality of the surrounding landscape [74,101]. *Cabruca*s that are located in a landscape where large areas are still covered by forests are better able to provide a habitat for some species [84,113,118,123,124]. The conservation status of these surrounding forest fragments is also a key factor for the conservation value of a cacao agroforest [83,124].

### 3.5. Evidence Gaps

Only 12 different classes of ES of a total of 67 listed in the CICES classification were reported to be affected by AF in Brazil. Yet, some of the remaining, unreported ES groups represent important research gaps, given the theoretical potential of AF to generate such key ES, including mediation of wastes and toxins (bio-remediation/filtration), storm protection, regulation of chemical water conditions, pollination and most of the cultural services

(physical, experiential, intellectual and spiritual interactions). Other classes of ES that were underrepresented (few studies), considering both the great potential that AF has to generate them and their key importance for society, include: surface water for drinking, water flow regulation, erosion control and pest and disease control.

#### 4. Discussion

Our results highlight a highly heterogeneous distribution of studies among the Brazilian biomes and administrative regions. Disproportional emphasis on intensely studied, small regions, particularly inside the Atlantic Forest, are not explained purely by its recognized importance to conservation for being Brazil's most deforested biome and biodiversity hotspot [125] or for housing 70% and 80% of Brazil's population and GDP, respectively [126]. In fact, the most intensely studied microregions may rather reflect socioeconomically important agroforestry systems that have historically attracted researchers' attention.

A bibliometric analysis of scientific papers published between 2005 and 2015 in Brazilian journals indexed in one of the main multidisciplinary databases (Scielo) helps us understand this heterogeneous distribution [68]. Mirroring our results, the Atlantic Forest was the most studied (30%), followed by Amazon (27%) and Caatinga (19%) [68]. The reduced number of studies in the Cerrado and Pampa biome, as well as the absence of agroforestry studies in the Pantanal, were also observed by other authors [68].

##### 4.1. Trends in the Agroforestry Literature

Our systematic map reveals that a large proportion of the literature published on AF systems' effects on ES production includes AF using highly soluble synthetic fertilizers, pesticides, or genetically modified organisms. This proportion is most probably related to the dominance of AF systems based on conventional agricultural models.

We found a focus on regulating (85%) and provisioning (13%) services, which is also demonstrated by another systematic map performed on the topic across Europe [49]. They found 54% of studies related to regulating and supporting services and 21% related to provisioning services. A similar and complementary systematic map found a slightly different result, where provisioning services were most frequently studied (42%) [50]. The greater proportion of either regulating or provisioning services is a general trend in agroecology, and also more broadly, ecosystem services literature [127–129].

Similar to the agroforestry literature in Brazil, decomposition and fixing processes and their effect on soil quality (soil quality), regulation of the chemical composition of the atmosphere and oceans (climate regulation) [50], and maintaining nursery populations and habitats (habitat & gene pool) [49] also predominate among studies on ES generated by AF across Europe [31]. Furthermore, these most frequently assessed services in AF also correspond to the most studied ones in the entire tropical region [31]. Specifically for Brazil, the bibliometric analysis cited above also detected soil quality as the most assessed topic (48%) among scientific articles on AF [68]. Considering all agroecological practices (not only AF), soil quality has been among the most studied ES globally [128], while in Brazil maintaining nursery populations and habitats (habitat & gene pool) registered a higher number of studies [129]. Since the very onset of AF research, more than three decades ago, there has been an emphasis on soil quality and biophysical interactions [130]. While over time the scope expanded to encompass socioeconomic issues and broader scales of analysis, there still remains a disproportionate focus on soil quality and maintaining nursery populations and habitats (habitat & gene pool). Studies on the regulation of the chemical composition of the atmosphere and oceans (climate regulation) have drawn attention more recently, especially using economic valuation models based on incentive mechanisms under debate within the United Nations Framework Convention on Climate Change UNFCCC [131]. A systematic review of ES research in Brazil found climate regulation as the second most common ES topic published in scientific articles between 2006–2017 [129].

Cultural ES were not explicitly reported by a single study on AF in Brazil, presumably due to the difficulties associated with their measurement [132]. However, of the 71 studies

reviewed in the European systematic map 17% were cultural ES, especially related to aesthetic values, recreation and ecotourism [49]. These and other cultural ES may also be important, yet under-researched in Brazil. In a 2019 systematic review of ES studies developed in Brazil, less than 2% were related to cultural ES [129]. In our reviews of theses and non-indexed publications, we found a substantial amount and diversity of research on sociocultural benefits generated by agroforestry in Brazil [133]. However, this important grey literature is currently fragmented or absent from incomplete databases, which hampers its discovery and analysis. It is impossible to ascertain whether the lack of cultural ES in our results is an actual research gap or due to preferential publication in outlets other than peer-reviewed international journals. Overall, the small number of publications related to cultural ES follows a worldwide trend [132].

#### 4.2. Effects on Ecosystem Services

By reviewing the general characteristics and drivers of the most studied services, some key insights emerge about the effects of AF. Despite the overall body of evidence that demonstrates positive effects of AF on soil quality and habitat & gene pool, its establishment and management must be carefully conducted to harness AF's full potential for synergies across multiple ES. Agroforestry does not always perform as well as undisturbed native vegetation with respect to habitat and soil quality, even ecological AF systems, as demonstrated in our results. However, ecological AF performs rather well compared to more simplified production systems such as average traditional agriculture (slash-and-burn), pasture, or crop monoculture, if both ecological and economic outcomes are accounted for. Yet, it cannot replace forests for the purpose of conserving a variety of important taxonomic groups [24,118,119].

The large body of evidence demonstrating the potential of AF for climate regulation also deserves to be highlighted here, since these systems are considered under the National Policy on Climate Change (Law No 12.187 of 2009) as a mitigation strategy of greenhouse gas emissions [76]. The Federal Decree No. 7.390 (2010), which regulates the implementation of Brazil's voluntary agreement, lists as a mitigation action an "increase in 4 million hectares of land covered by AF schemes, integrated with more intensive cattle raising activities (integrated agriculture/animal husbandry/forestry activities)" [134]. This regulation is coupled with the National Plan on Native Vegetation Restoration [73] and with specific credit lines focused on agroecology and forestry for small and medium farmers under the National Program for Strengthening Family Farming, which has practically been halted during the last couple of years. Considering the evidence gathered here and other reviews and meta-analyses we reaffirm this potential of soil conservation management applied in most AF systems to sequester carbon in long-term biospheric pools [21,22,35,39,135–138]. The potential for climate regulation has been a popular topic of AF research in the last few years [129,131]. However, recent dramatic environmental deregulation and inertia in environmental law enforcement highlights that robust evidence is powerless without strong advocacy [139].

#### 4.3. Implications for Future Research

The systematic map enabled us to identify the ES most frequently studied in the AF literature in Brazil, focused specifically on ecological AF systems. Further understanding the differences between ecological and conventional AF and their effect on ES production could provide important information for farmers, as well as for decision-makers dealing with payment for ecosystem services under the National Plan on Native Vegetation Restoration [73] and other policies. Moreover, another important step would be the development of an ecosystem-based approach to research AF systems regarding their effect on ecosystem functioning, to differentiate direct from indirect effects and thereby reveal the drivers of tradeoffs and synergies [140]. Understanding ES interaction could provide more complex and reliable information on AF's contribution to ES production and ecosystem functioning. Finally, meta-analyses on management effects would be another important

next step to assess how generalizable is the importance of the main drivers of AF to generate multifunctional synergies among regulating and provisioning services.

The potential of agroforestry for water quality enhancement has been getting increasing attention in scientific investigations [130,141]. Given the critical importance of land use in regulating water quantity and quality across Brazilian biomes, we are concerned that almost no attention has been paid to the effects of AF on hydrological ES, and none for the potential of these systems to attenuate pollution. These gaps need to be urgently addressed by future research not only because of the obvious importance of water as a strategic national and global resource but also because of the legal possibility to use agroforestry on small farms to protect river margins and springs [73]. The Brazilian legislation also allows for the implementation and management of agroforestry systems to recover other sensitive areas such as steep slopes and hilltops. Therefore, it is of particularly high priority to strengthen the evidence of the potential of different AF for erosion control, flood protection and maintenance of the hydrological cycle.

Another priority is to recommend and successfully implement AF systems that do not rely on agrochemicals and heavy external inputs. The proportion of studies focusing on pest and disease regulation in our review was relatively low, corroborating with other studies developed in Brazil [129]. A recent systematic review, which explored how agroecology and the ecosystem services framework have been adopted together in the scientific literature around the world, found pest control to be the most studied service, with soil quality second [128]. Due to Brazil's position as the world's largest user of agrochemicals [52], we suggest that ecological pest & disease control be made a priority in future research.

#### *4.4. Limitations of the Map and Potential Applicability*

Our results may be considered a relevant representation of the knowledge accessible in science so far on the topic in Brazil. However, it might still not be possible to extrapolate the evidence here gathered as an accurate reflection of the reality and use it as a base for important decision-making processes at the national scale. Some of the reasons are biases intrinsically associated with primary research, such as (1) the greater likelihood of “positive” results to be published in scientific articles compared to “no-effect” or negative results; (2) the focus on single interventions as the key to success, without considering context-dependent issues; (3) the extrapolation of results from restricted experiments as if they were universally applicable; (4) and the interpretation of a causal relationship when there is only evidence for correlation, which might be caused by unknown drivers [142]. Besides these, some weaknesses of the map result more directly from the reviewing phase, such as the interpretation and classification of the ES, the challenge of gathering evidence from different types of research approaches, the lack of a quality appraisal of the studies' evidence and the limitation of the single database used for the articles search. Moreover, our study focuses specifically on ecological AF, leaving aside AF with external synthetic inputs and GMOs. This assortment provides limited results considering the large variety of AF systems types developed in Brazil.

Nevertheless, the results can be very helpful to guide future research. Besides the identification of knowledge gaps, the evidence here gathered was organized by topics (type of ecosystem service, biogeographical region, etc.), which makes a comprehensive referencing material accessible for researchers, policymakers and practitioners interested in any of the topics encompassed here.

Finally, the CICES classification has been shown to better address ES classes and specifications found in the literature. Although it can cause some unfamiliarity for those used to the Millennium Ecosystem Assessment terminologies, we believe that CICES classes are potentially easier to be understood by policymakers and the general public. The next steps should broaden the benefits of agroforestry to be analyzed by the Nature's Contributions to People (NCP) classification, for their explicit consideration of learning, experiences, identities and maintenance of future options from a culturally inclusive perspective [143]. Agroforestry has major potential to enhance each of these.

## 5. Conclusions

The systematic map we presented provides an up-to-date view of the highly skewed geographical distribution of ecological AF published in the scientific literature and helps to assess the gaps of evidence related to AF effects on ES in Brazil. Land use decision-making and public policies concerned with soil quality, habitat & gene pool provision, or climate regulation should enable AF development, as revealed by the overwhelming number of scientific studies demonstrating positive effects of AF on these ES. Moreover, future research should fill the current gap of AF effects on water provision and regulation, given its critical importance for conservation and human well-being. In the same way, understanding the differences between ecological and conventional AF systems regarding their effect on ES production could be helpful in the design and implementation of local and regional projects and policies and support the decision making related to payment for ecosystem services.

In order to demonstrate the real potential of AF to attenuate or overcome the production-conservation trade-off and simultaneously promote human well-being, we need studies that jointly assess the provision of food and fiber with other important ecosystem services such as erosion control, flood protection and pest and disease control, especially those considering realistic resource limitations and other socio-ecological constraints. Understanding the interaction between different classes of ES may provide a broader picture of the AF effect on ecosystem functioning.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land11010083/s1>, File S1: Ecosystem Service terminology used in this systematic mapping, classified according to the Common International Classification of Ecosystem Services (CICES): [App1\_EcosystemServiceClasses.xlsx]; File S2: Summary of the 216 AF effects on ES documented by the 158 original journal articles included in this systematic mapping, their methodological approach, AF types, geographical and full bibliographic metadata [App2\_OriginalStudiesMetadata.xlsx].

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