Agriculture, Ecosystems and Environment 335 (2022) 108012

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Status and trends of pollination services in Amazon agroforestry systems

William Sabino[a,*], Luciano Costa[a], Tamires Andrade[a], Juliana Teixeira[a], Gustavo Araújo[a], André Luís Acosta[a], Luísa Carvalheiro[b], Tereza Cristina Giannini[a,c]

[a] Instituto Tecnológico Vale, Rua Boaventura de Silva 955, Belém, Pará 66055090, Brazil
[b] Departamento de Ecologia, Universidade Federal de Goiás, Goiânia, Goiás 74690900, Brazil
[c] Programa de Pós-Graduação em Zoologia, Universidade Federal do Pará, Belém, Pará 66075110, Brazil

ARTICLE INFO

Keywords:
Agricultural management
Agroecosystem
Bees
Beetles
Food production
Forested areas

ABSTRACT

With the growing demand for food production worldwide, natural landscapes are increasingly being replaced by agricultural areas, which directly affects biodiversity and local ecosystem services. Agroforestry systems, which are the intentional integration of trees and shrubs into crop and animal farming systems, are a more sustainable production approach that has been increasing in several forested areas around the globe. Here, we examine the trends of agroforestry in the Brazilian Legal Amazon and estimate the associated value of ecosystem services mediated by pollinators. Using data from 2006 and 2017, we detected an increase in agroforestry activity in the Amazon, both in the number (3.27%) and in the area (23.18%) of establishments. Crop production in forested areas increased by 45.61% in the same period, and the main products cultivated in both years were native products from the Amazon, such as açaí , Brazil nut and babassu. Although the crop data are from forested areas, all the five crops with the highest production value are associated with agroforestry in the Amazon. Pollination services also increased during the same period from US$73.3 to US$156.7 million (113.76%). In 2006, the value of pollination services corresponded to 44% of the total crop production, and it jumped to 64.43% in 2017. Bees and beetles were the two main groups of pollinators quoted for the analysed crops. Our estimates show the important contribution of pollinators to crop production in the Amazon forest. However, a growing loss of Amazon forest has been observed, and this can jeopardize pollinators and have detrimental consequences on food production in the near future. Public policies are urgently needed to encourage crop production in harmony with natural areas, combining the protection of forests and pollinators with food production.

1. Introduction

The global demand for food, feed, and fuel has increased continuously in recent years (Tilman et al., 2001; Nonhebel and Kastner, 2011), which has led to the expansion of agriculture and deforestation globally (Gibbs et al., 2010). The conservation of natural habitats is often seen as a bottleneck for agricultural productivity and vice versa (Koch et al., 2019; Kang and Akinnifesi, 2000), and especially in the last century, trees have been incrementally removed from the landscape because they are perceived as an obstacle to the intensification of agriculture (Eichhorn et al., 2006).

Developing synergies between the conservation of natural habitat and agricultural production is particularly relevant in the Brazilian Amazon, the world's largest tropical forest (Koch et al., 2019). Several products appreciated around the world are produced in the Amazon Forest, such as açaí (*Euterpe oleracea* Engel), Brazil nut (*Bertholletia excelsa* Bonpl) and cocoa (*Theobroma cacao* L.) (IBGE, 2017), which are essential for the economic development of this region with a low human development index (Rodrigues et al., 2009). However, the expansion of Amazon agriculture has come at the expense of native ecosystems (Campbell et al., 2018; Stabile et al., 2020), and it is essential to find sustainable practices that align food production and economic development for rural communities with forest conservation.

Agroforestry systems (AFSs) are a traditional practice of growing trees, along with crops and/or livestock, with the aim of increasing crop productivity, conserving soil and recycling nutrients while also producing firewood, fodder, fruits, and wood (Sanchez, 1995). The AFSs can play a key role in aligning biodiversity conservation with income generation in tropical forests (Perfecto et al., 1996). Adequate tree management in AFSs promotes effective ground cover and contributes to the maintenance and control of soil moisture (Aguiar et al., 2010), in addition to being important for CO_2 mitigation (Albrecht and Kandji,

* Corresponding author.
E-mail address: sabinobees@gmail.com (W. Sabino).

https://doi.org/10.1016/j.agee.2022.108012
Received 9 December 2021; Received in revised form 3 May 2022; Accepted 5 May 2022
Available online 16 May 2022

2003). In Brazil, AFSs have been shown to be an important strategy to increase productivity compared to traditional farming practices (Maia et al., 2021) and to provide complementary habitats for wild species, mitigating the effects of habitat loss (Cabral et al., 2021). This technique can enhance biodiversity and ecosystem service provision relative to conventional agriculture and could be a strategically beneficial land use type in rural planning (Torralba et al., 2016). Many models of agroforestry systems exist in the Amazon, from home gardens to orchards with mixed fruits. The most common model is practiced by small producers, which sustain families and communities (Tremblay et al., 2015).

Biotic crop pollination is an essential ecosystem service and critical to the world's food security (Klein et al., 2007; Potts et al., 2016a). The proportion of the total agricultural area occupied by insect pollinator-dependent crops has regularly increased from 1961 to 2016 (Aizen et al., 2019), and recently, the contribution of biotic pollination to crop yield has been valued at US$235–577 billion per year globally (Potts et al., 2016b). Pollinator-dependent crops worldwide make up more than 50% of the crop products traded in international markets (Silva et al., 2021a). In Brazil, the contribution of pollination services was first estimated as US$12 billion (year 2013; Giannini et al., 2015a), and a recent estimate reported US$11.79 billion annually (Wolowski et al., 2019). A first assessment showed that 85 Brazilian crops were dependent on pollinators (Giannini et al., 2015a), and recently, the ecosystem service of pollination was demonstrated to be essential for 35% of the analysed crops in Brazil (90–100% increase in crop production with the action of pollinators) (Wolowski et al., 2019). In the eastern Amazon, the total pollination service value is US$ 983.2 million per year, corresponding to 33% of the crop production value in one state in the Brazilian Amazon (Pará) (Borges et al., 2020). Despite the recent concern about the pollination situation worldwide, we still have large knowledge gaps about the role of many species in crop pollination, especially regarding the efficiency and effectiveness of pollinator species (Giannini et al., 2015b; Hipólito et al., 2020).

In addition to being the main pollinators of most agricultural crops, insects are important for pollination of wild plants (Klein et al., 2007; Ollerton et al., 2011; Lazarina et al., 2016). Among them, bees are the most important group of pollinators (Roubik, 1989; Potts et al., 2010, 2016a). They belong to the Apoidea superfamily, and it is estimated that there are more than four thousand genera, and approximately 25–30 thousand species distributed in different regions of the world (Michener, 2007), of which 20,555 have been described (Orr et al., 2021). Brazil has the greatest diversity of bees in the Neotropical region, with 1905 described species distributed in five families (Ascher and Pickering, 2019). Bees also constitute the main crop pollinators in Brazil (Giannini et al., 2015b), and a recent evaluation showed that 66.3% of crop pollinator species were bees, followed by beetles (9.2%), butterflies (5.2%), moths (5.2%), birds (4.4%), wasps (4.4%), flies (2.8%), bats (2%) and hemipterans (0.4%) (Wolowski et al., 2019).

Despite their importance, pollinators are globally under threat. Habitat fragmentation is one of the problems that can lead to decreasing species richness and abundance (Cane, 2001; Potts et al., 2010). However, other factors such as climate change, pesticides, alien species, pests and pathogens have also been considered possible drivers of pollinator decline (Potts et al., 2016b; IPBES, 2016). This decline is estimated to have a major economic impact on the agricultural sector, with catastrophic losses globally (Bauer and Wing, 2016). In countries such as the US, the decline in pollinators can directly translate into reduced yields or production for most agricultural crops (Reilly et al., 2020). For Brazil, it was demonstrated that climate change can affect crop pollinator bees, with detrimental economic impacts for most municipalities (Giannini et al., 2017). AFSs can provide habitat for pollinators and support pollination services by adding structural and functional diversity to agricultural landscapes (Jose, 2009), and it is an important strategy to jointly consider pollinator protection and food production. Especially in tropical forests, it is expected that crop pollination has a key role in food production (Potts et al., 2016a).

Our objective was to understand the panorama of AFSs in the Brazilian Amazon and evaluate crop pollination services in Amazon forested areas. We focused on answering four questions: (1) What are the status and trends of AFSs in the Amazon? (2) What crops are produced in forested areas in the Brazilian Legal Amazon, and what is their production value? (3) What dependence on pollinators do these crops have, and what is the value of pollination services for these crops? (4) Which pollinator species are reported for these crops? We hope to elucidate the status of pollination in Amazon AFSs, help pave the way for effective public policies, and encourage future research in this important system, especially for tropical agroforestry.

2. Material and methods

2.1. Study location

This study focused on the municipalities of the Brazilian Legal Amazon (BLA), which is a political-administrative area established by the Brazilian government by law in 1953 (Brasil, 1953). The area comprises the Brazilian states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins and the western part of the state of Maranhão. The BLA corresponds to 61% of the Brazilian territory, with an area of 5217,423 km^2 (Junior et al., 2011). Although most states in the BLA are dominated by humid tropical forests, significant areas of Tocantins, Maranhão, and Mato Grosso are occupied by Cerrado woodlands (Tyukavina et al., 2017).

2.2. Status and trends of AFSs in the Amazon

To assess the status and trends of AFSs in the BLA, we used municipality-level agricultural census data from the Brazilian Institute of Geography and Statistics (IBGE) with information on the number and area of each AFS established in 2006 and 2017 (IBGE, 2021). The agricultural census is the main and most complete statistical and territorial investigation of the country's agricultural production. The census investigates information about agricultural establishments and the agricultural activities developed in them, covering characteristics of the producer and establishment, economy and employment in rural areas, livestock, farming and agribusiness in all Brazilian territory (IBGE, 2021). The years 2006 and 2017 are the last two years with available data. The original data from IBGE (AFSs area and number) is collected through the application of a questionnaire to producers following the definition of agroforestry by IBGE: Area with forests (native or planted) that is also used for crops or animal grazing (crop-forest-livestock integration) (IBGE, 2017). The agricultural Census interviewed all farms (agricultural holdings) in Brazil (IBGE, 2017): 5175,636 farms in 2006 and 5068,445 farms in 2017. We also analysed the crops mostly used on AFSs in the BLA.

2.3. Crops produced and production value

As there is no information on each plant species used in AFSs, to estimate the economic value of crop production per municipality, we used indirect parameters through data about farming in forested areas to estimate the production value of each municipality within the study region (Table S1). The IBGE data has some gaps, mainly in the question of identifying whether the product comes directly from a forest or agroforestry. Nevertheless, we believe that these values are good indicators of the crop production value (CPV) in AFSs.

Since there are some differences between the years 2006 and 2017 in relation to some crops, for comparison, only the crops listed in both years were used. Thus, we excluded the crops of *Theobroma cacao* (cocoa), *Oenocarpus bacaba* (bacaba palm), *Dipteryx alata* (baru), *Eugenia dysenterica* (cagaita), *Myrciaria dubia* (camucamu), *Acmella oleracea* (jambu), *Acrocomia aculeata* (macauba palm) and *Byrsonima crassifolia* (nance) (present in 2017 data, but absent in 2006). However, these crops represent only 0.61% of the entire crop production value in 2017. The complete data for 2017 will be presented separately, with the inclusion of these crops.

2.4. Crop pollinator dependency and pollination service valuation

We searched for dependency values in the literature and classified them using the dependence pollination ratio (DR) proposed by Gallai

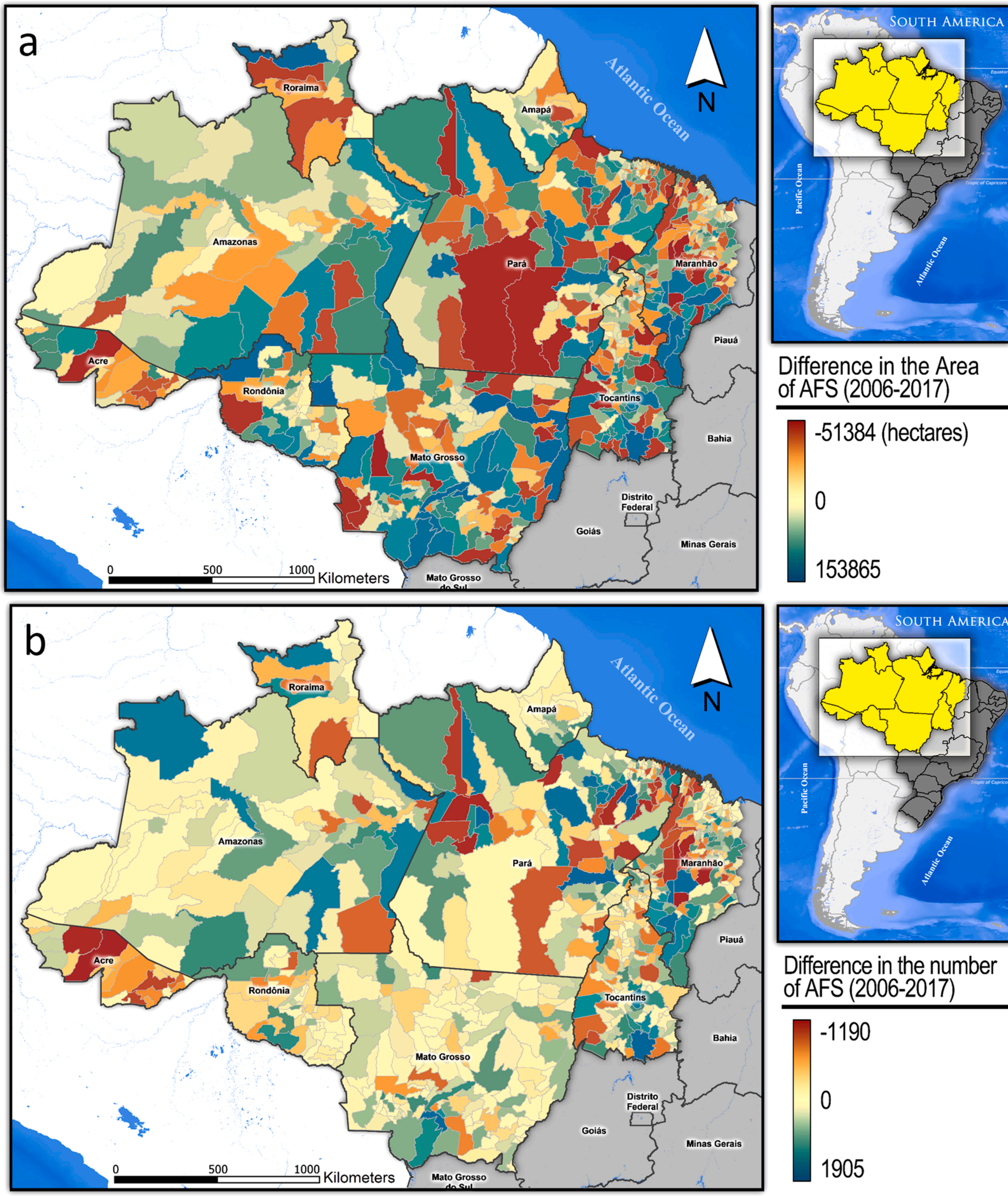

Fig. 1. Changes in (a) area and (b) number of agroforestry system (AFS) establishments per municipality in the Brazilian Legal Amazon between 2006 and 2017. Hot colors (red) indicates an increase, and the cold colors (blue) indicates a decrease in the parameters.
Source: Agricultural Census (IBGE, 2017).

and Vaissiere (2009) based on the rate of formation of fruits and/or seeds in the presence or absence of pollinators. The DR was categorized as (1) essential (DR= 0.95): 90–100% increase in production with the action of pollinators; (2) high (DR = 0.65): 40–90%; and (3) modest (DR = 0.25): 10–40%. Most DR values were calculated based on global studies (Klein et al., 2007) and Brazilian studies (Giannini et al., 2015a; Campbell et al., 2018; Wolowski et al., 2019; Borges et al., 2020). The category of "no increase" (DR= 0) was used when no dependence of the plant species by pollinators was reported or when the product did not result directly from pollination (e.g., leaves). When there was no information about the DR in a specific crop in the literature, we searched for this information for other plants in the same genus. To value pollination services (PSV) for each analysed crop, we multiplied the value of crop production by the dependence of each plant species on pollinators (Gallai and Vaissiere, 2009).

Table 1
Crops produced in forested areas in the Brazilian Legal Amazon, their dependence on pollinators, and their pollination service value in the study region.

Crop (English/Portuguese/ product)	Scientific name	Family	Dependence on pollinators	Dependence rate	Crop production value (2017) (US $1000)	Economic value of pollination service (2017) (US$1000)
1. Assai palm/Açaí/fruit	*Euterpe oleracea* Engel	Arecaceae	Great	0.65	197,602	128,441
2. Brazil nut/Castanha-do-Pará/almond	*Bertholletia excelsa* Bonpl	Lecythidaceae	Essential	0.95	20,699.4	19,664.4
3. Babassu palm/Babaçu/ coconut	*Orbignya phalerata* (Mart).	Arecaceae	Modest	0.25	10,257.1	2564.28
4. Babassu palm/Babaçu/ almond	*Orbignya phalerata* (Mart).	Arecaceae	Modest	0.25	7526.13	1881.54
5. Tucuma palm/Tucumã/ fruit	*Astrocaryum vulgare* (Mart.)	Arecaceae	Essential	0.95	1160	1102
6. * */Pequi/fruit	*Caryocar brasiliense* (Cambess.)	Caryocaraceae	Essential	0.95	887.101	842.736
7. Bacaba palm/Bacaba/fruit	*Oenocarpus bacaba* (Mart.)	Arecaceae	Great	0.95 *	901.943	586.251
8. Buriti palm/Buriti/ coconut	*Mauritia flexuosa* (L.f.)	Arecaceae	Essential	0.95	741.288	704.219
9. **/Bacuri/fruit	*Platonia insignis* (Mart.)	Clusiaceae	Essential	0.95	589.034	559.582
10. Cocoa/Cacau/almond	*Theobroma cacao* (L.)	Malvaceae	Essential	0.95	368.708	350.281
11. Peach palm/Pupunha/ coconut	*Bactris gasipaes* (Kunth.)	Arecaceae	Essential	0.95	305.167	289.897
12. Cupuassu/Cupuaçu/fruit	*Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum.	Malvaceae	Essential	0.95	229.673	218.185
13. **/Andiroba/seed	*Carapa guianensis* (Aubl.)	Meliaceae	Essential	0.95	201.292	191.231
14. Nance/Murici/fruit	*Byrsonima crassifolia* (L.) Kunth.)	Malpighiaceae	Essential	0.95	179.35	170.395
15. * */Cajarana/fruit	*Spondias dulcis* (Parkinson)	Anacardiaceae	Essential	0.95 *	125.156	118.895
16. * */Cumaru/seed	*Dipteryx odorata* (Aubl.) Forsyth f.	Fabaceae	Essential	0.95	82.5754	78.4546
17. * */Baru/almond	*Dipteryx alata* (Vog.)	Fabaceae	Essential	0.95	46.1309	43.8297
18. * */Copaíba/oil	*Copaifera langsdorffii* (Desf.)	Fabaceae	Essential	0.95	41.6177	39.5306
19. * */Mangaba/fruit	*Hancornia speciosa* (Gomes)	Apocynaceae	Essential	0.95	21.6205	20.5324
20. * */Ucuuba/almond	*Virola surinamensis* (Rol. ex Rottb.) Warb.	Myristicaceae	Essential	0.95	12.5763	11.9519
21. Murumuru palm/ Murumuru/seed	*Astrocaryum murumuru* (Mart.)	Arecaceae	Essential	0.95 *	7.742	7.34955
22. * */Cagaita/fruit	*Eugenia dysenterica* (Mart.) DC.)	Myrtaceae	Great	0.65	4.1921	2.72932
23. Macauba palm/ Macaúba/fruit	*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.)	Arecaceae	Great	0.65	0.64219	0.42813
24. * */Camucamu/fruit	*Myrciaria dubia* (Kunth) McVaugh	Myrtaceae	Modest	0.25	0.96329	0.24974
25. Assai palm/Açaí /Heart of palm	*Euterpe oleracea* Engel	Arecaceae	No increase	0	2295.81	0
26. Piassava/Piaçava/fiber	*Attalea funifera* (Mart.)	Arecaceae	No increase	0	302.259	0
27. Rubber tree/ Seringueira/clotted latex	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.	Euphorbiaceae	No increase	0	297.746	0
28. Buriti palm/Buriti/straw	*Mauritia flexuosa* L.f	Arecaceae	No increase	0	130.972	0
29. Rubber tree/ Seringueira/liquid latex	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.	Euphorbiaceae	No increase	0	23.5471	0
30. * */Sorva/nonelastic gum	*Couma utilis* ((Mart.) Muell. Arg.)	Apocynaceae	No increase	0	2.26552	0
31. * */Jambu/leaf	*Acmella oleracea* ((L.) R. K. Jansen)	Asteraceae	No increase	0	0.64219	0
32. Cassava/Maniçoba/ elastic gum	*Manihot esculenta* Crantz	Euphorbiaceae	No increase	0	0.64219	0
33. * */Maçaranduba/ nonelastic gum	*Manilkara huberi* (Ducke) A.Chev.	Sapotaceae	No increase	0	0.3211	0

*based on genus; ** no correspond name was found in English.

2.5. Crop pollinator species

The literature on pollinator species reported for each crop was reviewed using a keyword search ('scientific name of the plant species', 'popular name of the plant species', 'SAFs', 'agroforestry', 'crop pollination', 'pollination', 'pollinators', 'flower visitors', 'crop visitors' – and the variation of these words in Portuguese) on Web of Science and Google Scholar, followed by a review of references and cited articles. In

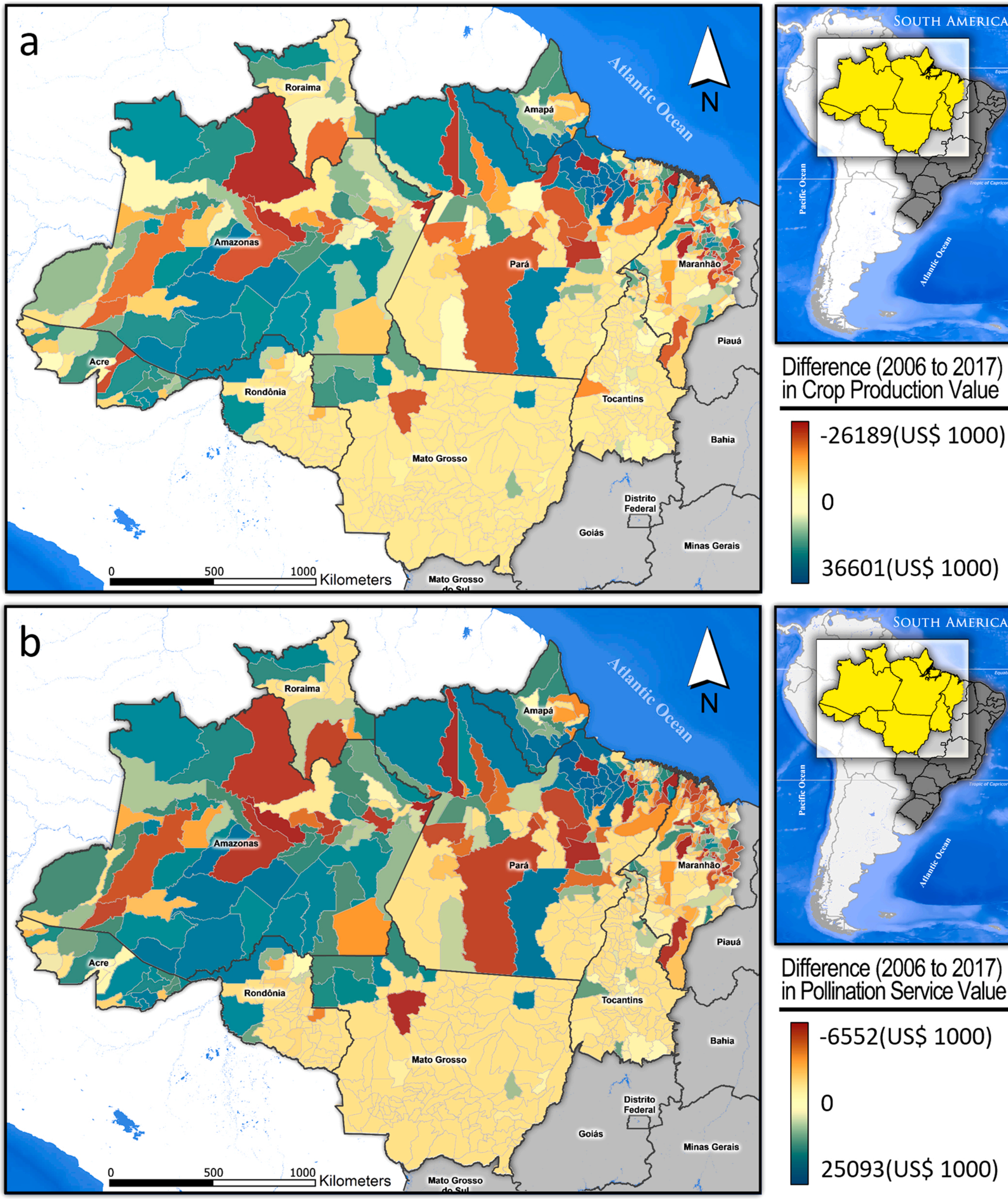

Fig. 2. Changes in (a) crop production value and (b) pollination service value in forested areas in the Brazilian Legal Amazon municipalities between 2006 and 2017. Hot colors (red) indicates an increase, and the cold colors (blue) indicates a decrease in the parameters
Source: Agricultural Census (IBGE, 2017).

total 33 studies were used, helping to understand the panorama of pollinators diversity associated with plants present in the IBGE list (Table S2 in supplemental material online).

The animal species were separated into floral visitors (if there was no indication of their role as effective pollinators), pollinators (if their role as effective pollinators was clearly stated) and undetermined (if the study did not make it clear whether it was a pollinator or a floral visitor). We considered only the effective pollinators here, since they are directly linked with the pollination service value. Nevertheless, all pollinators and visitors can be consulted in Table S2.

3. Results

3.1. Status and trends of AFSs in the Amazon

According to the census data, we observed an increase in the use of AFSs in the BLA between 2006 and 2017. There was an increase of 23.18% in the area (Fig. 1a) and an increase of 3.27% in the number (Fig. 1b) of AFSs established in the period analysed. Although the total number of AFSs increased, there was a decrease in the number of municipalities (N = 12; 1.55%) using this type of crop production.

The state of Pará had the highest number of AFS establishments, but the greatest growth in the period was observed for the state of Amapá (151.47%). The state with the greatest reduction in the number of establishments was Acre (65.76%), standing far from the second one, Tocantins (7.89%). Acre presented the highest reduction of AFS area (46.95%), in opposition to Roraima, which gained 75.88% more AFS area in the analysed period.

3.2. Crops produced and production value

We found 33 crops associated with forested areas in BLA. Twelve crops were Amazon palms (Arecaceae family, Table 1, Fig. S1), responsible for 90.28% of all production values in 2017 (Table 1). When analysing only the same crops between the years, we found that the total production value in forested areas increased by 45.61%, raising from US $167.3 million (2006) to US$243.5 million (2017) (Figs. 2a and S2). Analysing the more recent data (2017), the five crops with the highest crop production value (CPV) accounted for 97.28% of the total CPV: açaí (US$197.6 million), Brazil nut (US$20.7 million), Babassu coconut (US$10.3 million), Babassu almond (US$7.5 million), and palm heart (US$2.3 million) (Table 1).

3.3. Crop pollinator dependency and pollination service valuation

Of the 33 crops in forested areas analysed, 24 (73%) had some dependence on pollinators to the commercialized product. By estimating the pollination service value (PSV) of these crops (Fig. 2b), we found a value of US$73.3 million for 2006 (44% of CPV in that year) (Fig. S3a). Analysing only the same crops between the years, this value increased to US$156.7 million (64.36% of CPV) in 2017 (Fig. S3b). This changed corresponded to an increase of 113.76% in the PSV considering the analysed period.

The highest values obtained were for açaí (US$128.4 million), Brazil nut (US$19.7 million), Babassu coconut (US$2.6 million) and Babassu almond (US$1.9 million) (Table 1). Despite the high CPV of the palm heart derived from açaí palm, this crop was not considered here because its production is not directly related to animal pollination.

Analysing the more recent data (including all crops), among the 20 municipalities in the BLA with the highest CPV and PSV, 17 were in the state of Pará (Table 2). The result was strongly related to the açaí crop but also marginally related to other important products cultivated in the state, such as Brazil nut and cocoa.

Table 2
The twenty municipalities in the Brazilian Legal Amazon with the highest crop production value in forested areas and the pollination service value.

Municipality/State	Crop production value (2017) (US$1000)	Pollination service value (2017) (US$1000)
Curralinho/Pará	40,945.48	26,612.68
Afuá/Pará	22,513.23	14,264.35
Cametá/Pará	22,255.16	14,379.61
Barcarena/Pará	15,459.68	9994.69
Limoeiro do Ajuru/Pará	10,004.52	6503.81
Abaetetuba/Pará	7966.45	5099.39
Breves/Pará	7936.77	5019.42
Ponta de Pedras/Pará	7700.32	5003.56
Muaná/Pará	7160.00	4654.00
Gurupá/Pará	6274.52	4006.95
São Sebastião da Boa Vista/Pará	5614.19	3649.23
Acará/Pará	4362.58	2891.61
Viseu/Pará	4079.03	2758.98
Oeiras do Pará/Pará	4012.58	2615.63
Moju/Pará	3997.10	2595.52
Igarapé -Miri/Pará	3289.35	2121.95
Mazagão/Amapá	3211.29	2333.85
Macapá/Amapá	2670.32	1735.71
Chaves/Pará	2382.26	1540.50
Bacabal/Maranhão	2193.87	548.47

3.4. Crop pollinator species

Analysing only the same crops between the years, insects were the main pollinators cited. They were responsible for 84% of the total species evaluated as effective pollinators, followed by birds (12%) and bats (4%). The bees were prominent, making up 43% of the total number of species of crop pollinators, followed by beetles, which made up 15% of the total number of pollinator species (Fig. 3).

For five crops, we did not find information about effective pollinators in the literature: Murumuru palm (*Astrocaryum murumuru* Mart.), Sorva (*Couma utilis* (Mart.) Muell. Arg.) and Cajarana (*Spondias dulcis* Parkinson) (plants with a yield increased by pollinators), in addition to cassava (*Manihot esculenta* Crantz) and Jambu (*Acmella oleracea* (L.) R. K. Jansen), (plants with a yield no increased by pollinators). For most of these plants, the analysed literature provided information only about floral visitors (Martins et al., 2012; Jordão and Noronha, 2011; Souza et al., 2018) (Fig. 4).

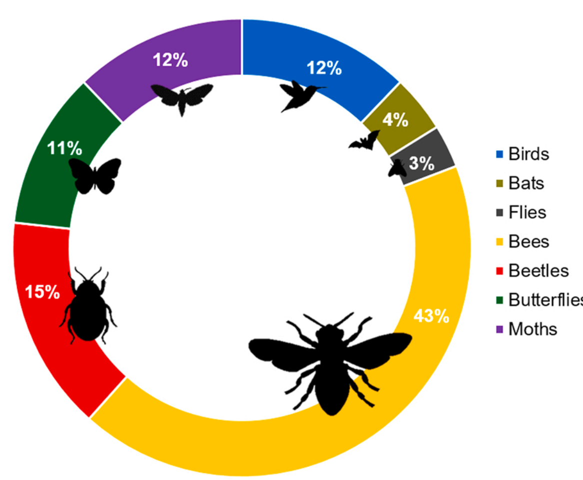

Fig. 3. Pollinator groups associated with crops present in forested areas in the Brazilian Legal Amazon. For the pollinator species reported for each crop, see Table S2.

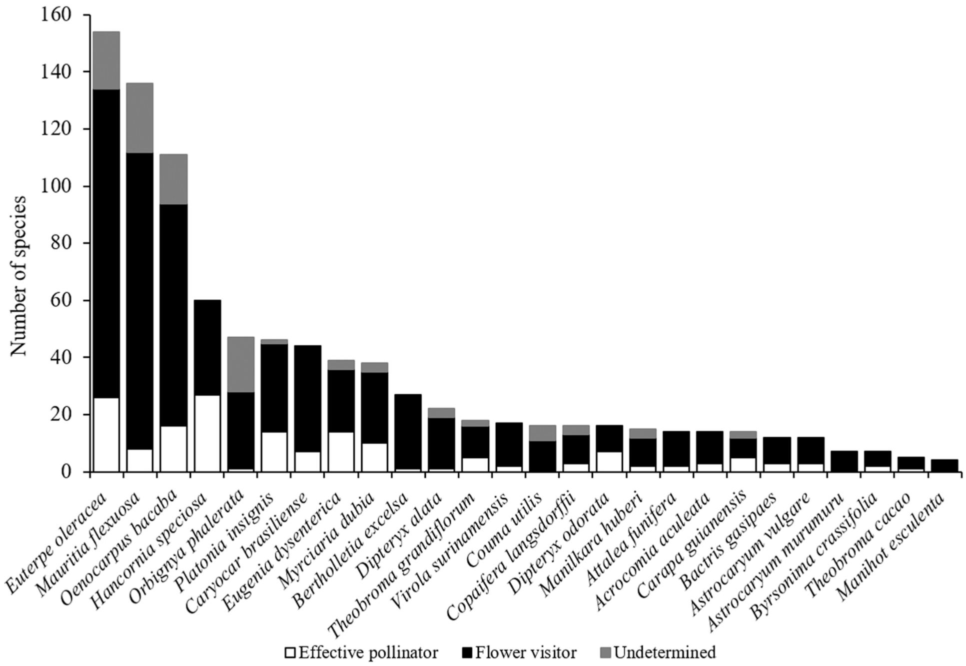

Fig. 4. Number of species of effective pollinators, floral visitors and species of indeterminate behavior (when the study does not make it clear whether it is a pollinator or visitor) associated with crops present in forested areas in the Brazilian Legal Amazon. For the pollinator species reported for each crop, see Table S2.

4. Discussion

Our results showed that there was an increase in the number (3.27%) and area (23.18%) of AFS establishments in the BLA between 2006 and 2017. The crop production in the forested areas analysed increased by 45.61% in the same period. A high number of crops were pollinator-dependent and pertained to the Arecaceae family (palm trees). We also found an increase in the value of pollination services considering the same period, and the percentage of the value of the pollination service in relation to the value of production increased from 44% to 67%. Insects, mainly bees and beetles, were the main pollinators.

4.1. Status and trends of AFSs in the Amazon

Especially in the Amazon region, farmers abandon annual fields to make room for açaí -dominated agroforests, preferring to purchase staple foods, such as manioc flour, rice, beans, and even corn used for animal food, instead of cultivating these crops (Steward, 2013). Despite this trend, we found a decrease in AFSs in some states in the Southern Amazon, a highly impacted area where forest losses accounted for 30% in the last year (Instituto Nacional de Pesquisas Espaciais (INPE), 2020). Associated with the latest public policies in Brazil, deforestation in the Amazon has increased in recent years. Brazil was responsible for 33% of the total loss of tropical forests in the world in 2019 (WRI, 2001), and during 2020, 11,000 km^2 of Amazon forests were lost (Instituto Nacional de Pesquisas Espaciais (INPE), 2020). This crescent loss of forest directly affects local communities, which strongly rely on ecosystem services for their subsistence (Foley et al., 2007).

The use of AFSs has grown in Brazil in recent years, especially in the Caatinga biome (Northeast region), in the South of the Mata Atlantica, and in isolated areas of the Cerrado (Central-West region), and in the Amazon (North region) biomes (Maia et al., 2021). Socioeconomic variables (land ownership, financing options, access to information and technical assistance) and agronomic variables (water resources availability and soil quality) are likely influencing the adoption of agroforestry systems in Brazilian municipalities (Schembergue et al., 2017). In addition, the ABC plan (Low Carbon Emissions in Agriculture) – as part of the National Climate Change Policy (PNMC) has been encouraging the use of AFSs in Brazil (Schembergue et al., 2017). Globally, AFSs has gained high attention in most of the developing countries for its potential for mitigating climate variability and increasing atmospheric CO_2 sequestration (Anderson and Zerriffi, 2012).

4.2. Crops produced and production value

The increase of the crop production value (CPV) in forested areas was notable between the years of 2006 and 2017. Recently, it was possible to observe a change in rural communities around the globe, and the topic of farmer-held agrobiodiversity has come into focus as a priority for conservation initiatives (Steward, 2013; Garrett et al., 2018). Changes in global and national policies and public awareness resulted in the search for an increase in agricultural production without deforestation (Schroth et al., 2016). New opportunities are emerging through the international markets that import these commodities, since sustainability is now a mainstream market concept that has moved from a corporate social responsibility to a strategic business issue (Millard, 2011). A large part of these efforts was probably due to concerns with climate change and the potential role of tropical forests as a carbon sink, which increased collective efforts, encouraged by national policies, for forest preservation and recovery (Rudel, 2012).

All the five crops with the highest CPV (97.28% of the total) are associated with AFSs in the Amazon (e.g. May et al., 1985; Costa et al., 2009; Campbell et al., 2018). The Arecaceae family was emphasized, being economically outstanding in the national market due to the total utilization of their products (Silva et al., 2021b). They also have an important role in the customs and culture of traditional communities (Brandão et al., 2019). Additionally, population growth in urban Amazonia has created a market for regionally preferred food sources, such as açaí fruit, which is a key regional staple food (Brondízio et al., 2002). We found that açaí was the main product in the forested areas of the Amazon, and 17 municipalities of the state of Pará presented the highest production values of açaí. Considering only Amazon forested areas, the açaí contribution was 80% of all crop production values. A previous work showed that Pará is the largest producer of açaí in Brazil, and the production of this fruit corresponds to one-third of the entire crop production in this state (Borges et al., 2020). Brazil nut and cocoa are also two crops that are cultivated in consonance with Amazon forest. Traditional cocoa management, for example, is mainly produced on a small scale by community-based farmers (Moguel and Toledo, 1999; Claus et al., 2018). Both açaí and cocoa are historically known as products that promote forest conservation (Peters et al., 1989). However, recent studies have shown that the intense management practices of both crops in AFSs can lead to a decline in local biodiversity. For example, cocoa forests are not only less diverse and less dense than secondary or primary forests of the region but also have severely impaired natural succession and gap dynamics in the Brazilian Atlantic forest (Rolim and Chiarello, 2004). A significant loss of local tree species richness and a trend towards floral impoverishment in Amazon floodplain forests were found under intense açaí production (Freitas et al., 2015).

4.3. Crop pollinator dependency and pollination service valuation

Considering the main crops produced in the Amazon forest, we found that a high number of them (73%) were pollinator-dependent. Pollination is an important service for crop production in the forested areas analysed. Our results show the importance of this ecosystem service for agricultural sector. Previous works showed that pollination service value corresponded to 30% of Brazilian crop production (141 crops) (Giannini et al., 2015a). A similar rate was reported for Pará, where 36 crops were analysed (Borges et al., 2020). Globally, the production of 48 of the 67 crops of the five leading commodities increases with pollinating animals (Klein et al., 2007). Of the 24 pollinator-dependent crops analysed here, 18 were recently determined to be important native species for socio-biodiversity, with high food value (Brasil, 2021). These crops enable the diversity of sustainable products that can generate income and ensure the quality of life of traditional communities and family farmers.

4.4. Crop pollinator species

The prevalence of bees as the main pollinators of the analyzed crops was expected, since bees are the largest group of crop pollinators associated with food production not only in tropical regions (Giannini et al., 2015b, 2020a; Wolowski et al., 2019) but also globally (Aizen et al., 2019). The reported decline in bees (Potts et al., 2016b) makes the protection of natural areas, which act as refuges for many bee species, more urgent (Brosi et al., 2008). Previous studies in the Amazon indicated that crescent forest fragmentation was associated with a decline in the abundance and diversity of native bees in remnants of native vegetation (Brown and Albrecht, 2001) and affects functional composition of bee communities in açaí plantations, with small-sized bees more susceptible to forest loss (Campbell et al., 2022). Many crops analysed here depend on wild pollinators, but the practice of pollinator management is rarely considered in the region (Venturieri, 2014; Campbell et al., 2018). The reduction of suitable habitats for bees will potentially increase as a result of climate change in the Eastern Amazon (Giannini et al., 2020b). The AFSs also provide resources for foraging and valuable nesting sites needed to maintain bee species, which are responsible for this important ecosystem service (Kay et al., 2020). Thus, agroforestry can be a useful alternative to combine the production of food with the protection of forests and bee pollinators. Moreover, intensive açaí management practices have impoverished pollinator communities in floodplains and have increased the frequency of antagonistic interactions on inflorescences in upland plantations (e.g., high ant densities) (Campbell et al., 2018). Thus, it is necessary that agroforestry practices be correctly applied to achieve sustainable production. Extensive farming practices and the maintenance of unmanaged forest areas surrounding the crop are pointed as important for a highly diverse flower-visitor community in the Amazon (Campbell et al., 2018).

The important role of beetles also needs to be emphasized since they were the second group among pollinators, mainly justified for the elevated number of Arecaceae plants. Pollination syndrome classified as cantharophilous was also found to be the second most important syndrome when analyzing 188 edible plant species used by traditional Amazon communities (Paz et al., 2021). Despite the importance of beetle in the pollination of one of the main Amazon products, such as açaí (Campbell et al., 2018; Bezerra et al., 2020), Brazilian legislation does not explicitly consider non-bee pollinators (Hipólito et al., 2021), thus neglecting this important pollinator group and its service (Lopes et al., 2021). Despite this, in Brazil, the lack of pollinator-relevant legislation (and a specific legislation for pollinators in AFSs) to provide sustainable conservation, mainly for the Amazon region, is notable (see Hipólito et al., 2021). A high diversity of pollinators (not only the abundance and the visitation rate) is essential for sustaining the pollination service, because of year-to-year variation in community composition (Kremen et al., 2002; Klein et al., 2003). Public policies for pollinators are urgent to ensure the maintenance of biodiversity and the services that they provide. Both biodiversity and ecosystem services remain chronically undervalued and largely missing in high-level discussions around the Sustainable Development Goals of the United Nations (Reyers and Selig, 2020).

Data on crop production, dependence on pollinators, and the main crop-pollinator species are scarce for the Amazon biome. Furthermore, our knowledge about pollination in AFSs in Brazil is limited (but see Maués and Venturieri, 1996; Maués et al., 1996; Maués and Santos, 1999; Maués et al., 2000; Maués and Couturier, 2002; Maués et al., 2008; Oliveira and Schlindwein, 2009; Dáttilo et al., 2012; Cavalcante, 2013; Bezerra et al., 2020), which demonstrates the large knowledge gap that exists in pollination and agroforestry practice. An example is cocoa, a commodity with high production value and scarce knowledge about its effective pollinators (Paz et al., 2021), especially in the Amazon (the main producer in Brazil). The mapping of pollinators in this scenario is important not only for conservation but also for more effective and targeted action by producers. Finally, we also highlight the ultimate importance of the national agricultural censuses, which are key to research on food production and to anticipate food vulnerability, especially considering the crescent impacts of global changes. For example, the IBGE census does not address all crop species, especially those consumed by traditional people (Paz et al., 2021). Moreover, more attention should be paid for AFS, since the data are mostly provided by farmers, and they may have different interpretations of what an AFS is (Maia et al., 2021).

5. Conclusion

AFSs have grown in recent years in number, area, and crop production in the BLA and have been acknowledged to promote the conservation of biodiversity with socioeconomic sustainability (Torralba et al., 2016). Additionally, the use of AFSs may be essential to safeguard crops from future climate change scenarios (Gomes et al., 2020) and enhance the diversity of agricultural production (Borges et al., 2020), contributing to local food security. The growing crop production in forested areas of the Amazon, especially of plants that are pollinator-dependent, makes it necessary to have public policies aimed at encouraging more sustainable practices, ensuring food production without compromising important ecosystem services. Studies on the valuation of important ecosystem services such as pollination are still scarce. This information is basic for planning more targeted actions by decision makers and farmers. In addition, specific studies about pollination in AFSs are urgent, aiming to protect pollinator species and their habitats. It is important for Brazil to have pollinator-relevant legislation that protects not only bees but also all other pollinators to safeguard food production.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank the Instituto Tecnológico Vale for project RBRS000603.26.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108012.

References

Aguiar, M.I., Maia, S.M.F., Xavier, F.A.D.S., Mendonça, E.S., Araújo Filho, J.A., Oliveira, T.S., 2010. Sediment, nutrient and water losses by water erosion under agroforestry systems in the semi-arid region in northeastern Brazil. Agrofor. Syst. 3, 277–289.

Aizen, M.A., Aguiar, S., Biesmeijer, J.C., Garibaldi, L.A., Inouye, D.W., Jung, C., Martins, D.J., Mendel, R., Morales, C.L., Ngo, H., Pauw, A., Paxton, R.J., Sáez, A., Seymour, C.L., 2019. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. Glob. Chang. Biol. 25, 3516–3527.

Albrecht, A., Kandji, S.T., 2003. Carbon sequestration in tropical agroforestry systems. Agric. Ecosyst. Environ. 99, 15–27.

Ascher, J.S., Pickering, J., 2019, Discover Life bee species guide and world checklist (Hymenoptera: Apoidea: Anthophila). ⟨http://www.discoverlife.org/mp/20q?guide=Apoidea_species⟩ (accessed 15 April 2021).

Anderson, E.K., Zerriffi, H., 2012. Seeing the trees for the carbon: agroforestry for development and carbon mitigation. Clim. Change 115, 741–757.

Bauer, D.M., Wing, I.S., 2016. The macroeconomic cost of catastrophic pollinator declines. Ecol. Econ. 126, 1–13.

Bezerra, L.A., Campbell, A.J., Brito, T.F., Menezes, C., Maués, M.M., 2020. Pollen loads of flower visitors to açaí palm (*Euterpe oleracea*) and implications for management of pollination services. Neotrop. Entomol. 49, 482–490.

Borges, R.C., Brito, R.M., Imperatriz-Fonseca, V.L., Giannini, T.C., 2020. The Value of Crop Production and Pollination Services in the Eastern Amazon. Neotrop. Entomol. 49, 545–556.

Brandão, F., Castro, F., Futemma, C., 2019. Between structural change and local agency in the palm oil sector: Interactions, heterogeneities and landscape transformations in the Brazilian Amazon. J. Rural Stud. 71, 156–168.

Brasil . Lei nº 1.806, de 06 de janeiro de 1953. Dispõe sobre o Plano de Valorização Econômica da Amazônia, cria a superintendência da sua execução e dá outras providências. Diário Oficial da União, Poder Executivo, Brasília, DF, 07 January 1953. Seção 1, 276 pp.

Brasil, 2021, Portaria interministerial MAPA/MMA nº 10, de 21 de julho de 2021. ⟨https://www.in.gov.br/en/web/dou/-/portaria-interministerial-mapa/mma-n-10-de-21-de-julho-de-2021–333502918⟩ (accessed 10 august 2021).

Brondízio, E.S., Safar, C.A., Siqueira, A.D., 2002. The urban market of açaí fruit (*Euterpe oleracea* Mart.) and rural land use change: ethnographic insights into the role of price and land tenure constraining agricultural choices in the Amazon estuary. Urban Ecosyst. 6, 67–97.

Brosi, B.J., Daily, G.C., Shih, T.M., Oviedo, F., Durán, G., 2008. The effects of forest fragmentation on bee communities in tropical countryside. J. Appl. Ecol. 45, 773–783.

Brown, J.C., Albrecht, C., 2001. The effect of tropical deforestation on stingless bees of the genus *Melipona* (Insecta: Hymenoptera: Apidae: Meliponini) in central Rondonia. Braz. J. Biogeogr. 28, 623–634.

Cabral, J.P., Faria, D., Morante-Filho, J.C., 2021. Landscape composition is more important than local vegetation structure for understory birds in cocoa agroforestry systems. For. Ecol. Manag. 481, 118704.

Campbell, A.J., Carvalheiro, L.G., Maués, M.M., Jaffé, R., Giannini, T.C., Freitas, M.A.B., Coelho, B.W.T., Menezes, C., 2018. Anthropogenic disturbance of tropical forests threatens pollination services to açaí palm in the Amazon river delta. J. Appl. Ecol. 55, 1725–1736.

Campbell, A.J., Lichtenberg, E.M., Carvalheiro, L.G., Menezes, C., Borges, R.C., Coelho, B.W.T., Freitas, M.A.B., Giannini, T.C., Leão, K.L., Oliveira, F.F., Silva, T.S. F., Maués, M.M., 2022. High bee functional diversity buffers crop pollination services against Amazon deforestation. Agric. Ecosyst. Environ. 326, 107777.

Cane, J.H., 2001. Habitat fragmentation and native bees: a premature verdict? Conserv. Ecol. 5, 3.

Cavalcante, M.C., 2013, Abelhas polinizadoras da castanheira-do-brasil (*Bertholletia excelsa*) cultivada na Amazônia central: papel do néctar e do entorno do plantio na polinização da cultura. Doctoral dissertation. Universidade Federal do Ceará. Fortaleza.

Claus, G., Vanhove, W., Van Damme, P., Smagghe, G., 2018. Challenges in cocoa pollination: the case of Côte d'Ivoire. In: Mokwala, P.W. (Ed.), Pollination in Plants. IntechOpen, London, pp. 39–58.

Costa, J.R., Castro, A.B.C., Wandelli, E.V., Coral, S.C.T., Souza, S.A.G.D., 2009. Silvicultural aspects of Brazil nut (*Bertholletia excelsa*) in agroforestry systems in Central Amazonia. Acta Amaz 39, 843–850.

Dáttilo, W., Martins, R.L., Uhde, V., Noronha, J.C., Florêncio, F.P., Izzo, T.J., 2012. Floral resource partitioning by ants and bees in a jambolan *Syzygium jambolanum* (Myrtaceae) agroforestry system in Brazilian Meridional Amazon. Agrof. Syst. 85, 105–111.

Eichhorn, M.P., Paris, P., Herzog, F., Incoll, L.D., Liagre, F., Mantzanas, K., Mayus, Sr, Moreno, G., Papanastasis, V.P., Pilbeam, D.J., Pisanelli, A., Dupraz, C., 2006. Silvoarable systems in Europe–past, present and future prospects. Agrofor. Syst. 67, 29–50.

Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P., 2007. Amazonia revealed forest degradation and loss of ecosystem goods and services in the Amazon Basin. Front. Ecol. Environ. 5, 25–32.

Freitas, M.A.B., Vieira, I.C.G., Albernaz, A.L.K.M., Magalhães, J.L.L., Lees, A.C., 2015. Floristic impoverishment of Amazonian floodplain forests managed for açaí fruit production. For. Ecol. Manag. 351, 20–27.

Gallai, N., Vaissiere, B.E., 2009. Guidelines for the Economic Valuation of Pollination Services at a National Scale. Food and Agriculture Organization of the United Nations,, Rome, p. 20.

Garrett, R.D., Koh, I., Lambin, E.F., De Waroux, Y.L.P., Kastens, J.H., Brown, J.C., 2018. Intensification in agriculture-forest frontiers: Land use responses to development and conservation policies in Brazil. Glob. Environ. Change 53, 233–243.

Giannini, T.C., Cordeiro, G.D., Freitas, B.M., Saraiva, A.M., Imperatriz-Fonseca, V.L., 2015a. The dependence of crops for pollinators and the economic value of pollination in Brazil. J. Econ. Entomol. 108, 849–857.

Giannini, T.C., Boff, S., Cordeiro, G.D., Cartolano Jr., E.A., Veiga, A.K., Imperatriz-Fonseca, V.L., Saraiva, A.M., 2015b. Crop pollinators in Brazil: a review of reported interactions. Apidologie 46, 209–223.

Giannini, T.C., Costa, W.F., Cordeiro, G.D., Imperatriz-Fonseca, V.L., Saraiva, A.M., Biesmeijer, J., Garibaldi, L.A., 2017. Projected climate change threatens pollinators and crop production in Brazil. PLoS One 12, e0182274.

Giannini, T.C., Alves, D.A., Alves, R., Cordeiro, G.D., Campbell, A.J., Awade, M., Bento, J.M.S., Saraiva, A.M., Imperatriz-Fonseca, V.L., 2020a. Unveiling the contribution of bee pollinators to Brazilian crops with implications for bee management. Apidologie 51, 406–421.

Giannini, T.C., Costa, W.F., Borges, R.C., Miranda, L., Costa, C.P.W., Saraiva, A.M., Fonseca, V.L.I., 2020b. Climate change in the Eastern Amazon: crop-pollinator and occurrence-restricted bees are potentially more affected. Reg. Environ. Change 20, 1–12.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. PNAS 107, 16732–16737.

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Fernandes, R.B.A., Fernandes Filho, E.I., Schulte, R.P.O., 2020. Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil. Agric. Ecosyst. Environ. 294, 106858.

Hipólito, J., Nunes, D.O., Ángel-Coca, C., Mahlmann, T., Galetto, L., Viana, B.F., 2020. Performance, effectiveness, and efficiency of honeybees as pollinators of *Coffea arabica* (Gentianales, Rubiaceae). Neotrop. Entomol. 49, 501–510.

Hipólito, J., Coutinho, J., Mahlmann, T., Santana, T.B.R., Magnusson, W.E., 2021. Legislation and pollination: Recommendations for policymakers and scientists. PECON 19, 1–9.

IBGE, 2017, Censo Agropecuário 2017. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro. ⟨https://censos.ibge.gov.br/agro/2017/⟩ (accessed 9 March 2021).

IBGE, 2021, Sobre o Censo Agropecuário. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro. ⟨https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/21814–2017-censo-agropecuario.html?edicao=23751&t=o-que-e⟩ (accessed 25 July 2021).

Instituto Nacional de Pesquisas Espaciais (INPE)., 2020, PRODES—Monitoramento da Floresta Amazônica Brasileira por Satélite. INPE database. ⟨http://www.obt.inpe.br/prodes/index.php⟩ (accessed 15 July 2021).

IPBES, 2016, Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production, in: Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., Aizen, M.A., Cunningham, S.A., Eardley, C., Freitas, B. M., Gallai, N., Kevan, P.G., Kovács-Hostyánszki, A., Kwapong, P.K., Li, J., Li, X., Martins, D.J., Nates-Parra, G., Pettis, J.S., Rader, R., Viana, B.F. (Eds.), Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 36 p.

Jordão, A.L., Noronha, A.D.S., 2011, Visitantes florais e potenciais polinizadores da mandioca (Manihot esculenta Crantz) em localidades do estado do Amapá. In: Congresso Brasileiro de Mandioca, Maceió. Mandioca: fonte de alimento e energia: anais. Maceió: ABAM: SBM.

Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor. Syst. 76, 1–10.

Junior, M.G.B., Contini, E., Navarro, Z., 2011, Caracterização da Amazônia Legal e Macrotendências do Ambiente Externo; Embrapa Estudos e Capacitação: Brasília, Brazil.

Kang, B.T., Akinnifesi, F.K., 2000. Agroforestry as alternative land-use production systems for the tropics. Nat. Res. Forum 24, 137–151.

Kay, S., Kühn, E., Albrecht, M., Sutter, L., Szerencsits, E., Herzog, F., 2020. Agroforestry can enhance foraging and nesting resources for pollinators with focus on solitary bees at the landscape scale. Agrofor. Syst. 94, 379–387.

Klein, A.M., Steffan–Dewenter, I., Tscharntke, T., 2003. Fruit set of highland coffee increases with the diversity of pollinating bees. Proc. R. Soc. Lond. B Biol. Sci. 270, 955–961.

Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., S. Cunningham, A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R. Soc. Lond. 274, 303–313.

Koch, N., zu Ermgassen, E.K., Wehkamp, J., Oliveira Filho, F.J., Schwerhoff, G., 2019. Agricultural productivity and forest conservation: Evidence from the Brazilian Amazon. Am. J. Agric. Econ. 101, 919–940.

Kremen, C., Williams, N.M., Thorp, R.W., 2002. Crop pollination from native bees at risk from agricultural intensification. PNAS 99, 16812–16816.

Lazarina, M., Sgardelis, S.P., Tscheulin, T., Kallimanis, A.S., Devalez, J., Petanidou, T., 2016. Bee response to fire regimes in Mediterranean pine forests: The role of nesting preference, trophic specialization, and body size. Basic Appl. Ecol. 17, 308–320.

Lopes, A.V., Portoa, R.G., Cruz-Neto, O., Peres, C.A., Viana, B.F., Giannini, T.C., Tabarelli, M., 2021. Neglected diversity of crop pollinators: Lessons from the world's largest tropical country. PECON 19, 500–504.

Maia, A.G., Eusebio, G.S., Fasiaben, M.D.C.R., Moraes, A.S., Assad, E.D., Pugliero, V.S., 2021. The economic impacts of the diffusion of agroforestry in Brazil. Land Use Policy 108, 105489.

Martins, K., Raposo, A., Klimas, C.A., Veasey, E.A., Kainer, K., Wadt, L.H.O., 2012. Pollen and seed flow patterns of *Carapa guianensis* Aublet.(Meliaceae) in two types of Amazonian forest. Genet. Mol. Biol. 35, 818–826.

Maués, M.M., Venturieri, G.C., 1996, Ecologia da polinização do bacurizeiro (Platonia insignis Mart.) Clusiaceae. Embrapa Amazônia Oriental, Belém.

Maués, M.M., Venturieri, G.C., Souza, L.A., Nakamura, J., 1996, Identificação e técnicas de criação de polinizadores de espécies vegetais de importância econômica no estado do Pará. Embrapa Amazônia Oriental, Belém.

Maués, M.M., Santos, L.F.C., 1999, Biologia floral do parapará (Jacaranda copaia (Aublet) D. Don Bignoniaceae). In Embrapa Amazônia Oriental-Artigo em anais de congresso (ALICE), in: Simpósio Silvicultura na Amazônia Oriental: contribuições do Projeto Embrapa/DFID, Belém.

Maués, M.M., Sousa, L.A., Miyanaga, R., 2000, Insetos polinizadores do cupuaçuzeiro (Theobroma grandiflorum (Willd. Ex Sprengel) Schum-Sterculiaceae) no Estado do Pará, Brasil. Embrapa Amazônia Oriental, Belém.

Maués, M.M., Couturier, G., 2002. Biologia floral e fenologia reprodutiva do camu-camu (*Myrciaria dubia* (HBK) McVaugh, Myrtaceae) no Estado Pará, Brasil. Braz. J. Bot. 25, 441–448.

Maués, M.M., Oliveira, P.E.A., Kanashiro, M., 2008. Pollination biology in *Jacaranda copaia* (Aubl.) D. Don.(Bignoniaceae) at the" floresta nacional do tapajós", central Amazon, Brazil. Braz. J. Bot. 31, 517–527.

May, P.H., Anderson, A.B., Frazão, J.M.F., Balick, M.J., 1985. Babassu palm in the agroforestry systems in Brazil`s Mid-North region. Agrof. Syst. 3, 275–295.

Michener, C.D., 2007. The Bees of the World, second ed..,. The Johns Hopkins Univ. Press,, Baltimore. Maryland.

Millard, E., 2011. Incorporating agroforestry approaches into commodity value chains. Environ. Manag. 48, 365–377.

Moguel, P., Toledo, V.M., 1999. Biodiversity conservation in traditional coffee systems of Mexico. Biol. Conserv. 13, 11–21.

Nonhebel, S., Kastner, T., 2011. Changing demand for food, livestock feed and biofuels in the past and in the near future. Livest. Sci. 139, 3–10.

Oliveira, R., Schlindwein, C., 2009. Searching for a manageable pollinator for acerola orchards: the solitary oil-collecting bee *Centris analis* (Hymenoptera: Apidae: Centridini). J. Econ. Entomol. 102, 265–273.

Ollerton, J., Winfree, R., Tarrant, S., 2011. How many flowering plants are pollinated by animals? Oikos 120, 321–326.

Orr, M.C., Hughes, A.C., Chesters, D., Pickering, J., Zhu, C.D., Ascher, J.S., 2021. Global patterns and drivers of bee distribution. Curr. Biol. 31, 451–458.

Paz, F.S., Pinto, C.E., Brito, R.M., Imperatriz-Fonseca, V.L., Giannini, T.C., 2021. Edible Fruit Plant Species in the Amazon Forest Rely Mostly on Bees and Beetles as Pollinators. J. Econ. Entomol. 114, 710–722.

Perfecto, I., Rice, R.A., Greenberg, R., Van der Voort, M.E., 1996. Shade coffee: a disappearing refuge for biodiversity: shade coffee plantations can contain as much biodiversity as forest habitats. BioScience 46, 598–608.

Peters, C.M., Balick, M.J., Kahn, F., Anderson, A.B., 1989. Oligarchic forests of economic plants in Amazonia: utilization and conservation of an important tropical resource. Conserv. Biol. 3, 341–349.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W.E., 2010. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25, 345–353.

Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T. (Eds.), 2016a, The assessment report on pollinators, pollination and food production of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn, Germany.

Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T., Aizen, M.A., Biesmeijer, J.C., Breeze, T. D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016b. Safeguarding pollinators and their values to human well-being. Nature 540, 220–229.

Reilly, J.R., Artz, D.R., Biddinger, D., Bobiwash, K., Boyle, N.K., Brittain, C., Brokaw, J., Campbell, J.W., Daniels, J., Elle, E., Ellis, J.D., Fleischer, S.J., Gibbs, J., Gillespie, R. L., Gundersen, K.B., Gut, L., Hoffman, G., Joshi, N., Lundin, O., Mason, K., McGrady, C.M., Peterson, S.S., Pitts-Singer, T.L., Rao, S., Rothwell, N., Rowe, L., Ward, K.L., Williams, N.M., Wilson, J.K., Isaacs, R., Winfree, R., 2020. Crop production in the USA is frequently limited by a lack of pollinators. Proc. R. Soc. B. 287, 20200922.

Reyers, B., Selig, E.R., 2020. Global targets that reveal the social–ecological interdependencies of sustainable development. Nat. Ecol. Evol. 4, 1011–1019.

Rodrigues, A.S., Ewers, R.M., Parry, L., Souza, C., Veríssimo, A., Balmford, A., 2009. Boom-and-bust development patterns across the Amazon deforestation frontier. Science 324, 1435–1437.

Rolim, S.G., Chiarello, A.G., 2004. Slow death of Atlantic forest trees in cocoa agroforestry in southeastern Brazil. Biodivers. Conserv. 13, 2679–2694.

Roubik, D.W., 1989. Ecology and Natural History of Tropical Bees. Cambridge Tropical Biology Series. Cambridge University Press,.

Rudel, T.K., 2012. The human ecology of regrowth in the tropics. J. Sustain. 31, 340–354.

Sanchez, P.A., 1995. Science in agroforestry. Agrofor. Syst. 30, 5–55.

Schembergue, A., Cunha, D.A., Carlos, S.M., Pires, M.V., Faria, R.M., 2017. Sistemas agroflorestais como estratégia de adaptação aos desafios das mudanças climáticas no Brasil. Rev. Econ. Soc. Rural 55, 9–30.

Schroth, G., Garcia, E., Griscom, B.W., Teixeira, W.G., Barros, L.P., 2016. Commodity production as restoration driver in the Brazilian Amazon? Pasture re-agro-forestation with cocoa (*Theobroma cacao*) in southern Para. Sustain. Sci. 11, 277–293.

Silva, F.D.S., Carvalheiro, L.G., Aguirre-Gutiérrez, J., Lucotte, M., Guidoni-Martins, K., Mertens, F., 2021a. Virtual pollination trade uncovers global dependence on biodiversity of developing countries. Sci. Adv. 7, eabe6636.

Silva, A.J.B., Sevalho, E.S., Miranda, I.P.A., 2021b. Potencial das palmeiras nativas da Amazônia Brasileira para a bioeconomia: análise em rede da produção científica e tecnológica. Cienc. Florest. 31, 1020–1046.

Souza, A.P.S., Junior, H.B.S., Jardim, M.A.G., Pereira, R.N., 2018. Visitantes florais de palmeiras em Floresta Ombrófila Densa Aluvial na Amazônia Oriental. Biota Amaz. 8, 1–4.

Stabile, M.C., Guimarães, A.L., Silva, D.S., Ribeiro, V., Macedo, M.N., Coe, M.T., Pinto, M.T., Moutinho, P., Alencar, A., 2020. Solving Brazil's land use puzzle: Increasing production and slowing Amazon deforestation. Land Use Policy 91, 104362.

Steward, A., 2013. Reconfiguring agrobiodiversity in the Amazon estuary: market integration, the Açaí trade and smallholders' management practices in Amapá, Brazil. Hum. Ecol. 41, 827–840.

Tilman, D., Fargione, J., Wolff, B., D'antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284.

Torralba, M., Fagerholm, N., Burgess, P.J., Moreno, G., Plieninger, T., 2016. Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agric. Ecosyst. Environ. 230, 150–161.

Tremblay, S., Lucotte, M., Revéret, J.P., Davidson, R., Mertens, F., Passos, C.J.S., Romana, C.A., 2015. Agroforestry systems as a profitable alternative to slash and burn practices in small-scale agriculture of the Brazilian Amazon. Agrof. Syst. 89, 193–204.

Tyukavina, A., Hansen, M.C., Potapov, P.V., Stehman, S.V., Smith-Rodriguez, K., Okpa, C., Aguilar, R., 2017. Types and rates of forest disturbance in Brazilian Legal Amazon, 2000–2013. Sci. Adv. 3, e1601047.

Venturieri, G.C., 2014. Plano de manejo para os polinizadores do açaizeiro Euterpe oleracea (Arecaceae). In: Yamamoto, M., Oliveira, P.E., Gaglianone, M.C. (Eds.), Uso sustentavel e restauracao da diversidade dos polinizadores autoctones na agricultura e nos ecossistemas relacionados: Planos de Manejo. Funbio, Rio de Janeiro.

Wolowski, M., Agostini, K., Rech, A.R., Varassin, I.G., Maués, M., Freitas, L., Carneiro, L. T., Bueno, R.O., Consolaro, H., Carvalheiro, L., Saraiva, A.M., Silva, C.I., 2019. Relatório temático sobre polinização, polinizadores e produção de alimentos no Brasil. REBIPP,, Espiríto Santo.

WRI, 2001, We Lost a Football Pitch of Primary Rainforest Every 6 Seconds in 2019. ⟨https://www.wri.org/insights/we-lost-football-pitch-primary-rainforest-every-6-seconds-2019⟩ (accessed 26 July 2021).