frontiers | Frontiers in Forests and Global Change

TYPE Original Research
PUBLISHED 03 November 2022
DOI 10.3389/ffgc.2022.1028129

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to People and Forests, a section of the journal Frontiers in Forests and Global Change

RECEIVED 25 August 2022
ACCEPTED 11 October 2022
PUBLISHED 03 November 2022

CITATION
Alves RP, Levis C, Bertin VM, Ferreira MJ, Cassino MF, Pequeno PACL, Schietti J and Clement CR (2022) Local forest specialists maintain traditional ecological knowledge in the face of environmental threats to Brazilian Amazonian protected areas. *Front. For. Glob. Change* 5:1028129. doi: 10.3389/ffgc.2022.1028129

Local forest specialists maintain traditional ecological knowledge in the face of environmental threats to Brazilian Amazonian protected areas

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There is a concern that environmental threats that result in local biodiversity loss compromise traditional peoples' livelihoods and their traditional ecological knowledge (TEK). Nonetheless, studies usually only analyze how people's characteristics influence TEK. Here, we investigated both: how the personal characteristics of local specialists (forest experience, gender, and origin) and environmental threats (deforestation, mining, and fires) influence some components of TEK associated with forests. From 2015 to 2019, we conducted free-listing interviews with 208 specialists from 27 communities in and near 10 protected areas (PAs) in Brazilian Amazonia. We recorded forest trees and palms that the specialists mentioned as used, managed, and traded. Plant knowledge was variable, since 44% of the 795 ethnospecies were mentioned only once. Using Mixed-Effects Models, we identified that people with longer forest experience and men tended to cite more used and traded ethnospecies. Women knew more about human food, while men knew more about construction and animal food. Specialists with greater forest experience knew more about protective management and planting. Specialists living in communities influenced by mining cited fewer used ethnospecies, and those in more deforested communities cited proportionally more planting. Environmental threats had smaller effects on TEK than personal characteristics. The components of TEK that we assessed highlight the forest's great utility and the importance of management of PAs to maintain biodiversity and traditional people's livelihoods. The communities' stocks of TEK persisted in the face of environmental threats to PAs, highlighting the resistance of traditional peoples in the face of adversities. This quantitative approach did not show the trends that are generally imagined, i.e., loss of forest TEK, but demonstrates that if we want to change the Amazonian development model to keep the forest standing, knowledge exists and resists.

KEYWORDS

Amazon forest, deforestation, fires, mining, ethnobotany, traditional people

Introduction

Traditional ecological knowledge (TEK) is a dynamic integrated system of knowledge, practice, and beliefs about people's relationships with other living beings, with each other, and with their environment (Berkes, 1993). Recently, the IPBES/5/15 (2017) expanded this definition to highlight Indigenous Peoples: "Indigenous and local knowledge systems are in general understood to be dynamic bodies of integrated, holistic, social and ecological knowledge, practices and beliefs pertaining to the relationship of living beings, including people, with one another and with their environments." Both definitions emphasize that the knowledge systems have different components and are dynamic. In Berkes (1993) definition, the term "traditional" should be interpreted as a link with the past of the knowledge transmitted through generations, creating a continuity that combines innovation with convention (Sajeva et al., 2019). Communities with a strong bond with their past often have a strong bond with their territories (Sajeva et al., 2019). Thus, TEK and its holders are essential for protecting their territories, conserving biodiversity, and facing current environmental crises. Their contributions are locally based, regionally manifested, and globally relevant (Brondízio et al., 2021). Understanding how external drivers affect TEK and its dynamics can help design more inclusive and locally supported conservation strategies.

In general, TEK varies due to both human characteristics and environmental conditions. TEK tends to increase with age due to the accumulation of experiences, although after a certain age TEK can diminish (Albuquerque et al., 2011). Gender also influences TEK. Some studies show that men know more about forest resources, while women understand more about species occurring close to their homes and in domestic areas (Stagegaard et al., 2002; Voeks, 2007; Albuquerque et al., 2011). A person's origin is also important. It is reasonable to assume that people who are natives of a given traditional community (i.e., born in the local community) will have more contact with local natural resources and thus know more about local species. However, non-native or migrants' livelihoods may change, with the inclusion of traditional activities learned in new locations, and their life trajectory becomes more relevant than their origin (Oestreicher et al., 2014). Thus, with time the knowledge of natives and non-natives may not differ (Mikołajczak et al., 2019). Regardless of the origin and other personal characteristics, it is common to find local specialists recognized in their community as experts in certain subjects, such as regional plants and/or animals (Albuquerque et al., 2014). We can assume that local specialists represent the stock of knowledge of their community. These knowledge stocks are relevant for restoring practices that have fallen into disuse, especially in contexts undergoing profound transformations.

In Amazonia, negative anthropic impacts have been intensifying in the last decades. From 2012 to 2020, legal mining increased from 52,974 to 58,432 localities, with the majority (51,890) in Brazilian Amazonia (RAISG, 2020a). In 2020, 4,472 illegal mining localities were identified, with more than 50% (2,576) in Brazil (RAISG, 2020a). The use of large-scale fires to open new fronts for exploitation has intensified. From 2001 to 2019, 13% of Amazonia (or 1.1 million km^2) was affected by fires, with a higher percentage in Brazilian Amazonia (17%) (RAISG, 2020a). Mining, fires, and other large-scale human activities generate deforestation. From 2000 to 2018, accumulated deforestation reached 513,016 km^2 (RAISG, 2020a). In 2021, deforestation affected 13,235 km^2 of Brazilian Amazonia, representing an increase of 22% compared to the previous year (INPE, 2021).

Negative synergies between deforestation, widespread use of fire, and climate change suggest that Amazonia is heading toward irreversible ecosystem change (Lovejoy and Nobre, 2018; Boulton et al., 2022). Amazonia is losing globally important ecosystem services (Levis et al., 2020), directly affecting human communities that depend on forest resources. Environmental changes that reduce resource availability and contaminate water and soils alter traditional people's ways of life, even encouraging them to migrate, and are likely to affect their TEK (Tang and Gavin, 2016; Brondízio et al., 2021). Even residents of protected areas (PAs) are not exempt from the consequences of environmental changes. Although anthropogenic pressures are more intense outside the PAs, they have also increased within them (Barber et al., 2014; Geldmann et al., 2019).

There is a close relationship between tropical forests' destruction and biodiversity and cultural loss (Ramirez, 2007). Thus, we expect that environmental threats that cause losses of diversity reduce people-plant interactions, resulting in a loss of knowledge. However, despite several studies suggesting that environmental threats negatively affect TEK, few test their direct effects (Tang and Gavin, 2016). A test like this is better done with hypothesis-based approaches (Gaoue et al., 2017), but requires simplification of complex scenarios into measurable and comparable information. Testing more integrative ethnobotanical hypotheses is complex since the ethnobotanical dataset usually involves non-independent observations due to socio-relational links between informants requiring advanced statistical approaches (Gaoue et al., 2021).

Here, we adopt a hypothesis-based approach and control the sampling bias of non-independent observations to test whether: (i) more experienced men and people native to the community know more about forest plants; and (ii) environmental threats (deforestation, mining, and fires) diminish TEK, as they affect the availability of plant resources and may change the livelihoods of traditional peoples. We used Mixed-Effects Models to evaluate how the personal characteristics of forest specialists that live in and around PAs and the environmental threats to these communities influence some components of TEK associated with forests. We used components of TEK that are easily quantified: knowledge about forest plants and their uses; and practices to manage these plants and their ecosystems.

Materials and methods

Ethical procedures and authorizations

This study was approved by the Ethics Committee for Research with Human Beings (CEPSH; CAAE: No. 67404317.2.0000.0006), the Biodiversity Information and Authorization System (SISBio No. 58609/1 and 53041.2), the Department of Climate Change and Management of Protected Areas/Secretary of the State of Amazonas for the Environment (DEMUC/SEMA No. 10/2017), the Institute for Forestry Development and Biodiversity of the State of Pará (Ideflor-bio No. 11/2019), and the National Indigenous Foundation (FUNAI–CR Madeira: Processes No. 1.396.762/2016 and 001/APIJ/2016). Before starting the research, we presented our investigation proposal to the local community leaders who approved the study and signed general authorizations. Before each interview, specialists signed the Free, Prior and Informed Consent form. This study is registered in the National System of Genetic Resource Management and Associated Traditional Knowledge (SisGen No. AEA864D).

Study areas and environmental threats

Our study involved 27 communities located in or around 10 PAs in Brazilian Amazonia: Caxiuanã National Forest (in Portuguese: *Floresta Nacional*—FLONA), Humaitá FLONA, Tapajós FLONA, Tapirapé-Aquiri FLONA, Tefé FLONA, Amanã Sustainable Development Reserve (in Portuguese: *Reserva de Desenvolvimento Sustentável*—RDS), Piagaçu-Purus RDS, Uatumã RDS, Rio Ouro Preto Extractive Reserve (in Portuguese: *Reserva Extrativista*—RESEX), and Jiahui Indigenous Land (in Portuguese: *Terra Indígena*—TI) (**Figure 1**; see **Supplementary Table 1** for community information). All areas were created more than 17 years ago and have established management councils.

Nine PAs have resident human populations. The exception is Tapirapé-Aquiri FLONA controlled by the multinational mining company Vale, where we interviewed residents of a nearby farming settlement. We also interviewed residents around Tefé FLONA and Piagaçu-Purus RDS. We consider as "surroundings" the area within 10 km of the PAs, as this area includes communities strongly influenced by the PAs' management plans. The Jiahui TI residents are Indigenous Peoples, belonging to the Jiahui ethnic group of the Tupi language trunk, and the residents of the other PAs are considered local communities; many are *ribeirinhos* who are descendants of Indigenous, African, and European peoples. Because local ecological knowledge can vary across an area as large as Amazonia, we considered this set of local knowledge systems to be TEK. In general, community residents in and around the studied PAs engage in various subsistence and trade activities, such as farming, extraction of non-timber forest products (e.g., Brazil nuts, assai, and babassu), and fishing.

All communities suffer environmental threats, such as deforestation, followed by fires, and mining, with variations in the type and intensity of threats depending on the available natural resources, geographic location and local political contexts. In general, PAs closer to the southern Amazonian deforestation arc suffer more types of environmental threats and in greater intensities (**Supplementary Figure 1**). For our analyses, we estimated the environmental threats at the community level.

We delimited an area of 31,400 hectares, considering a radius of 10 km from a reference point near the center of each community. We characterized these areas with respect to historical environmental threats: areas of deforestation, areas of fires, and the number of mining occurrences (**Supplementary Table 1**). Deforestation was estimated based on accumulated data of clear-cuts that occurred from 1988 to 2019, recorded by the Amazon Deforestation Monitoring Program (PRODES), which uses LANDSAT, DMC, and CBERS satellite images, mapping annual deforestation in areas larger than 6.25 hectares (INPE, 2019). To characterize fires, we used the 2000–2019 consolidated burned areas based on data

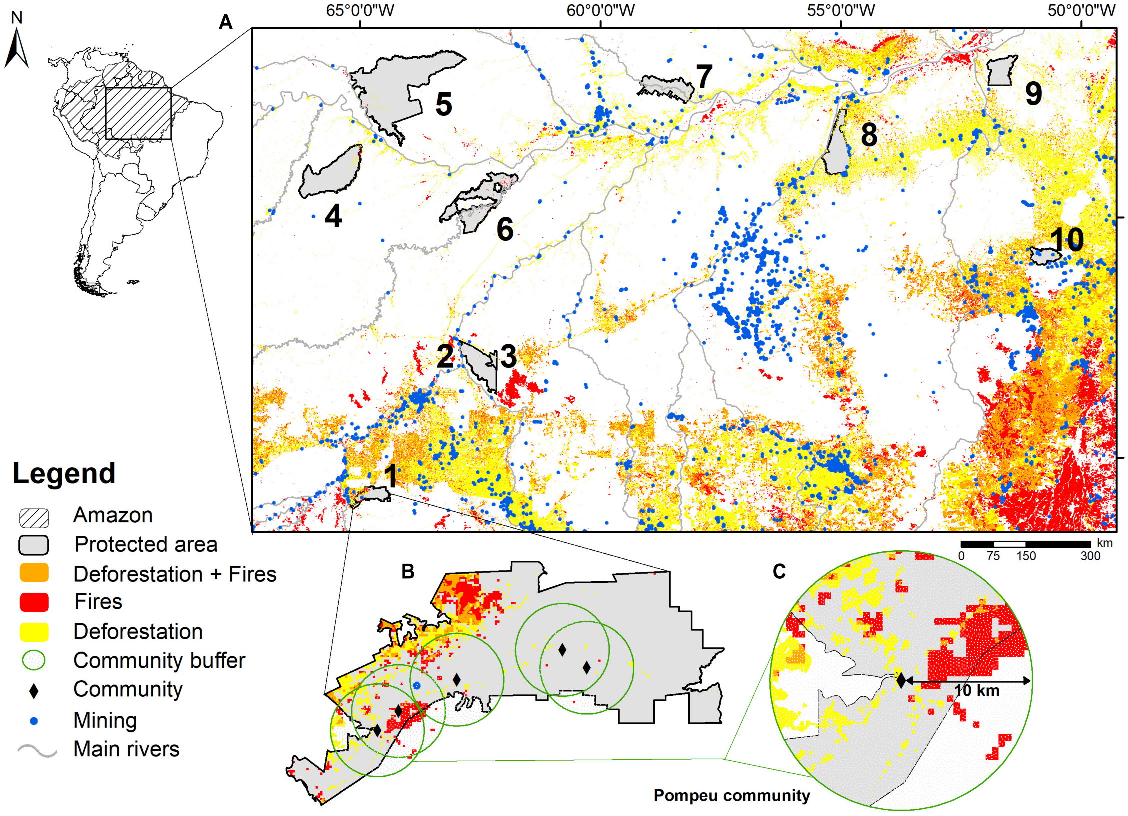

FIGURE 1
(A) Location of the 10 protected areas studied and their environmental threats context. Gray polygons correspond to protected areas: 1 Rio Ouro Preto RESEX; 2 Humaitá FLONA; 3 Jiahuí TI (smaller polygon overlaping Humaitá FLONA); 4 Tefé FLONA; 5 Amanã RDS; 6 Piagaçu-Purus RDS; 7 Uatumã RDS; 8 Tapajós FLONA; 9 Caxiuanã FLONA; 10 Tapirapé-Aquiri FLONA. Environmental threats: in yellow—accumulated deforestation from 1988 to 2019; in red—2000–2019 consolidated burned areas; in orange—deforestation and fires overlap; in blue—legal and illegal mining in 2020. **(B)** Example of the estimates of environmental threats at the community level in Rio Ouro Preto RESEX. **(C)** Detailed Pompeu community example. Some communities' 10 km radius overlapped and/or are beyond the PAs' limits.

from the MCD64A1/MODIS (Moderate Resolution Imaging Spectroradiometer) with a resolution of 500 m (RAISG, 2020b). To characterize mining, we counted the occurrences of currently active legal and illegal mining in the Amazon Network of Georeferenced Socio-Environmental Information database (RAISG, 2020b).

Interviews and data standardization

From 2015 to 2019, we interviewed 208 key-specialists who know well and use *terra-firme* (upland) forests, as identified by local leaders and other community members. We interviewed at least three and a maximum of 49 specialists per PA. The number of specialists interviewed varied according to the number of communities visited per PA (one to five communities/PA), time, and availability of specialists to participate in the study. The interviews involved the socioeconomic characterization of the specialists, free listing of the trees and palms with utility to them, and the characterization of their uses, management, and trade. We standardized popular names mentioned in free lists, eliminating variants of the same name and regionalisms. In our analyses, we considered popular names—hereafter ethnospecies—that correspond to the species and/or varieties mentioned in the lists (see **Supplementary material** and **Supplementary data** for botanical correspondence).

We organized the plant uses cited in the interviews into six categories, based on the UseFlora (2021) classification with adaptations: 1. Human food—consumed as food by people, including condiments, colorings, and drinks; 2. Medicine—used for therapeutic purposes; 3. Construction—wood and thatch used for civil construction, naval, and furniture manufacturing; 4. Manufacturing—handicrafts, decorative instruments or articles, toys, cosmetic production (soap and perfume), paper, caulking for canoes, repellents, fertilizers, rope, cigarettes, and fuel; 5. Animal food—consumed by animals, including use for hunting and fishing; and 6. Others. Among the uses, we analyzed trade separately because trade relations often go beyond local exchanges and may be more subject to external influence.

We organized the management practices that favor the plants in the landscape into eight categories, following Levis et al. (2018): 1. Removal of non-useful plants—cleaning around preferred plants to reduce competition; 2. Protection of useful plants—keeping plant seedlings, juveniles, and adults alive through several practices; 3. Disperser attraction—attracting seed-dispersing animals; 4. Human transportation—humans disperse seeds and transplant seedlings intentionally or non-intentionally from one place to another; 5. Phenotypic selection—human selection for specific phenotypes of plants; 6. Fire management—use of fire as a land management tool that increases resources, such as light, and soil nutrients; 7. Planting—intentionally planting seeds and seedlings in cultivated landscapes; and 8. Soil improvement—improving soil structure and fertility. For many ethnospecies, the specialists mentioned several types of uses and management that corresponded to different categories. In the analyses, we considered all categories.

Data analyses

We evaluated the characteristics of specialists and environmental threats as factors that may influence TEK associated with the forest. As characteristics of the specialists, we considered gender, origin (if the informants were native to their communities or not), and forest use experience (in years), which correlates with the specialist's age (t = 24.459, df = 205, r = 0.86, p-value < 0.001). As environmental threats, we analyzed deforestation, fires, and mining at the community level, estimated as previously explained.

As our study was done at a relatively large-scale, encompassing 27 communities in 10 PA across Amazonia, we chose to use the number of specialists' citations of used, managed, and traded ethnospecies (ethnospecies richness) as a proxy for TEK associated with the forest. To further qualify TEK, we also considered the composition of use and management categories as response variables. For all variables (richness of used, managed, and traded ethnospecies; and the composition of used and managed ethnospecies) the sample unit was the collaborating specialist. We summarized the compositions with the first two axes of a Principal Coordinate Analysis (PCoA), using the Bray–Curtis distance applied to percent abundances of categories per specialist.

We used mixed-effects models in our analyses. When evaluating the response of the richness of ethnospecies to the characteristics of specialists and the environmental threats predictors, we assumed the Negative Binomial distribution for residuals and log link and used Generalized Linear Mixed-Effects Models (GLMM). When evaluating the response of the composition of use and management categories (PCoA axes), we assumed the Normal distribution for residuals and used Linear Mixed-effects Models (LMM). In all models, we included communities (N = 27) as a random factor, and we estimated the global statistical significance of the models by likelihood-ratio tests. The analyses were performed in R version 4.1.2 (R Core Team, 2021), using packages vegan (Oksanen et al., 2020), lme4 (Bates et al., 2015), MuMIN (Barton, 2022), car (Fox and Weisberg, 2019), visreg (Breheny and Burchett, 2017), and gplots (Warnes et al., 2020).

Results

Local forest specialists and their knowledge

The forest specialists were an average of 51 years old, with the youngest 16 and the oldest 85. Most specialists (82%) were men, and 68% were natives of the place where they live. Among the 67 non-native specialists, 63 were from other Amazonian regions, and four were from another Brazilian region. A total of 25% of the specialists had used the forest for more than 51 years (median = 40 years, first quartile = 28 years, and third quartile = 51 years), with a minimum use time of 2 years and a maximum of 74 years. In communities located in floodplains, few people use *terra-firme* forests, and the community indicated younger specialists with less experience.

The 208 specialists cited 795 useful ethnospecies, with 44% mentioned only once. On average, the specialists cited 35 ethnospecies, with a minimum of 10 and a maximum of 117. The 12,501 citations of uses were categorized: 29% construction, 25% human food, 16% manufacturing, 16% animal food, 13% medicine, and 1% other uses, which cover ritualistic, touristic, ornamental, animal medicine, poison, shade, and communication in the forest. Considering the six use categories, 32% of the 795 useful ethnospecies had one type of use, 31% two types, and 37% three or more types.

The specialists cited 496 ethnospecies as managed (62% of used ethnospecies), among which 41% were mentioned only once. On average, the specialists cited 18 managed ethnospecies, with a minimum of two and a maximum of 69. The 5,862 management citations were categorized: 37.5% protection, 33.2% removal of competitors, 24.4% planting, 1.9% human dispersal, 1.8% soil improvement, 0.7% phenotypic selection, 0.3% fire management, and 0.2% disperser attraction. Considering the eight management categories, 35% of the 496 managed ethnospecies received one type of management, 29% two types, and 36% three or more types.

The specialists cited 157 ethnospecies as traded (20% of the ethnospecies used), among which 55% were cited only once. On average, the specialists cited four traded ethnospecies, with a minimum of zero and a maximum of 22. To illustrate the ethnospecies list, we present the 10 most cited ethnospecies by forest specialists (**Table 1**). For these ethnospecies, it was possible to match popular and scientific names, some with multiple matches (Supplementary material). In addition to being the best known, these ethnospecies were more frequently mentioned as managed and traded. Their cited uses contemplated all use categories, except for Itaúba and uxi, which had no use categorized as "other." Their cited management practices included five or more categories.

Environmental threats to communities

The communities studied have an average of 8% of their delimited area deforested (minimum 0.2% and maximum 84.7%). An average of 3.3% of the area was burnt, with four PAs without large-scale fires and a maximum of 27.5% burnt area. Five communities are under the influence of one mining locality and one community of two mining localities.

How specialists' characteristics and environmental threats influence forest traditional ecological knowledge

Both specialists' characteristics and environmental threats influenced used ethnospecies richness. The specialists' characteristics also influenced the composition of use categories. People with longer forest experience and men tended to mention more ethnospecies, while mining negatively influenced used ethnospecies richness. Men cited relatively more construction (PCoA1) and animal food (PCoA2) ethnospecies, while women cited relatively more human food (PCoA2) (Table 2 and Figures 2A, 3A).

Both specialists' characteristics and environmental threats influenced the composition of management categories. Specialists with more forest experience cited relatively more protecting (PCoA1) and planting (PCoA2), and less removal of competitors (PCoA1 and PCoA2). Deforestation positively influenced planting while it negatively influenced the citations of removal of competitors (PCoA2; Table 2 and Figures 2B, 3B).

The specialists' characteristics influenced traded ethnospecies richness, but environmental threats did not. Specialists with more forest experience and men cited more traded ethnospecies (Figures 2C, 3C). See Supplementary Table 2 for the model statistics.

Discussion

Our results support our hypothesis that men and more experienced specialists know more used and traded forest plants, but these characteristics did not influence citations of managed plants. Our hypothesis that native specialists know more about forest plants was not supported, possibly because the non-native specialists are mainly from other Amazonian regions. Our hypothesis that environmental threats negatively affect TEK was found only for mining, which had a small effect on used ethnospecies richness. Surprisingly, deforestation favored citations for planting. The specialists' personal characteristics were stronger predictors of TEK than environmental threats. We argue that time is relevant for each community's stocks of knowledge, and the divisions of tasks contribute to maintain the forest as a predominantly male domain. This TEK is available in the communities and its holders resist environmental threats, contributing to conserving their livelihoods and PAs.

Long-term forest traditional ecological knowledge

Our results show that specialists' forest TEK is extremely variable since 44% of 795 used ethnospecies were cited only once. If, on the one hand, the large number of ethnospecies cited only once suggests dynamic forest knowledge that is constantly being built, on the other hand, the list of the 10 most cited ethnospecies by forest specialists (Table 1) demonstrates shared knowledge about species with a long-term relationship with Amazonian human populations. Among the 10 most

TABLE 1 The 10 most cited ethnospecies by the 208 forest specialists in 10 protected areas across Brazilian Amazonia.

Ethnospecies	Family	Species	Used	Managed	Traded
Castanha	Lecythidaceae	*Bertholletia excelsa* Bonpl.	187	183	100
Piquiá	Caryocaraceae	*Caryocar villosum* (Aubl.) Pers.	187	143	23
Itaúba	Lauraceae	*Mezilaurus itauba* (Meisn.) Taub. ex Mez; *M. duckei* van der Werff; *M. lindaviana* Schwacke & Mez	177	62	17
Açaí-solitário	Arecaceae	*Euterpe precatoria* Mart.	159	153	76
Copaíba	Fabaceae	*Copaifera* sp.; *C. piresii* Ducke; *C. duckei* Dwyer; *C. martii* Hayne; *C. multijuga* Hayne	159	133	35
Bacaba	Arecaceae	*Oenocarpus bacaba* Mart.; *O. distichus* Mart.	151	128	15
Buriti	Arecaceae	*Mauritia flexuosa* L.f.	148	113	16
Uxi	Humiriaceae	*Endopleura uchi* (Huber) Cuatrec.	141	101	13
Babaçu	Arecaceae	*Attalea speciosa* Mart.	139	84	13
Tucumã	Arecaceae	*Astrocaryum aculeatum* G. Mey.	128	96	26

For each ethnospecies we present the botanical correspondence, the number of specialists that cited uses, management, and trade of the ethnospecies.

TABLE 2 Correlations between original variables and the two main axes of the Principal Coordinate Analysis (PCoA) performed to summarize the composition (percent abundance per specialist, using the Bray–Curtis distance) of (A) use and (B) management categories.

(A) Use	PCoA1	PCoA2	(B) Management	PCoA1	PCoA2
Construction	0.99	−0.09	Protection	−0.98	0.14
Human food	−0.30	0.89	Removal	0.83	0.55
Medicine	−0.17	0.22	Planting	0.40	−0.89
Manufacturing	−0.39	−0.48	Fire management	−0.04	−0.14
Animal food	−0.41	−0.61	Phenotypic selection	0.12	−0.07
Others	−0.16	0.13	Human dispersal	0.16	−0.01
			Disperser attraction	−0.12	−0.04
			Soil improvement	0.03	−0.18

Proportion of explained variance by the two PCoA axes: Use Goodness of fit (GOF) = 0.43 and management GOF = 0.69. We used both axes in the linear mixed-effects models.

cited species, eight have populations with some degree of domestication (Clement, 1999); and nine have been found in archaeobotanical records of archeological sites in Amazonia (Cassino et al., 2021). The use and management of these species by pre-colonial Indigenous Peoples during thousands of years of occupation of Amazonia transformed landscapes, creating forests with high richness and abundance of species useful to humans, which persist in the present (Levis et al., 2017, 2018). Thus, the knowledge shared by the forest specialists reflects a solid long-term history of interactions among people and plants in Amazonia.

Effects of the specialists' personal characteristics on their forest traditional ecological knowledge

We found that the stocks of TEK depend on the knowledge of community elders. We confirmed that older people with longer forest experience cited more used and traded ethnospecies. Hanazaki et al. (2013) pointed out several explanations for this pattern, covering factors such as time, changes in lifestyle, the disinterest of young people and environmental changes that affect resource availability. In our study, although we have not explored this wide range of factors, we found that time is relevant to accumulate experiences. Time also reflected the incentives and cycles of commercial resource exploitation, with more experienced specialists having a greater knowledge of traded plants.

Our results also showed that mature forest is a predominantly male domain. The differences in landscape use reflect the division of tasks based on gender (Voeks, 2007), which can also influence the composition of use categories (Stagegaard et al., 2002). We found that men understand more about construction and animal food plants (mainly related to hunting), while women know more about human food. The role of women as caregivers and primary healthcare providers for family and community results in a greater knowledge of food and medicinal plants (Voeks, 2007).

The origin of specialists did not influence the components of TEK that we evaluated. Oestreicher et al. (2014) studied the livelihood activities and land-use patterns of migrants from two periods to the Tapajós region (that we also studied). They found that families who have been in the region for several generations tend to adopt traditional activities (e.g., collecting and selling non-timber products). In our study, 92% of non-native specialists are from other regions of Amazonia, making native and non-native forest TEK more similar. Furthermore, non-native specialists are likely to be living in the PAs enough time to incorporate new knowledge and become recognized by other community members as forest specialists.

Effects of environmental threats on forest traditional ecological knowledge

Only mining had a small effect on ethnospecies richness. Mining is a far-reaching socio-environmental threat. In the Trombetas and Carajás regions (the latter we also studied), mining has increased forest loss significantly up to 70 km beyond mining lease boundaries, due to urban development and the establishment of infrastructure for processing and transporting minerals (Sonter et al., 2017). In Amazonia, illegal mining is small-scale and often practiced by non-natives, who migrate to the localities to explore the resource until it is depleted, leaving severe environmental and social impacts (Veiga and Hinton, 2002; Basta et al., 2021; Siqueira-Gay and Sánchez, 2021). Mining also causes social impacts that include threats to social justice, loss of cultural livelihoods, and economic vulnerability due to dependence on the mining industry as a source of employment (Suopajärvi et al., 2017). These changes can reduce forest resource availability, their uses and consequently the citations of plants known to be useful by forest specialists.

We found that deforestation favored planting citations. In PAs, the increase in deforestation increases the demand for restoration projects, which involve mainly planting of seedlings and reforestation based on agroforestry systems

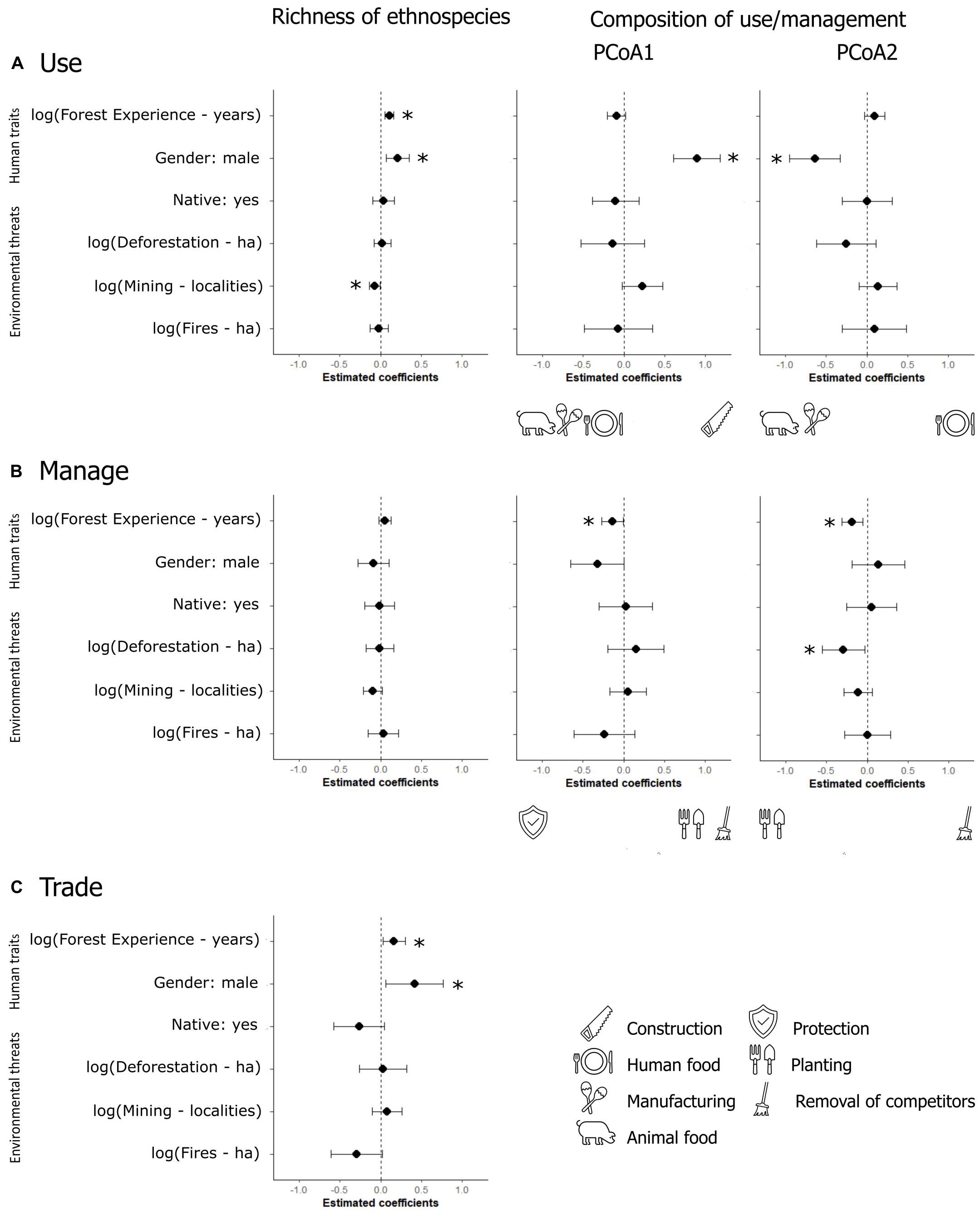

FIGURE 2
Relationships among ethnospecies richness and composition of use and management categories, and forest specialists' characteristics (forest experience, gender, and origin) and environmental threats (deforestation, mining, and fires). The standardized beta coefficients and 95% confidence intervals of explanatory variables of generalized linear mixed-effects models are shown for: **(A)** used ethnospecies richness (R^2 = 0.20; $p < 0.001$) and composition of use categories (PCoA1, R^2 = 0.48, $p < 0.001$ and PCoA2, R^2 = 0.35, $p < 0.001$); **(B)** managed ethnospecies richness (R^2 = 0.21, p = 0.014) and composition of management categories (PCoA1, R^2 = 0.26, $p < 0.001$ and PCoA2, R^2 = 0.25, $p < 0.001$); **(C)** traded ethnospecies richness (R^2 = 0.27, $p < 0.001$). The composition of use and management categories are expressed by the first two axes of the PCoA. The variables that most contributed to the PCoA axis are represented below the results of the models (see Table 2 for the PCoA attributes loadings). *Indicates statistically significant variables at 5% significance level.

(da Cruz et al., 2021). These active strategies are adequate for lands that have undergone intensive use, resulting in compacted soil, excessive loss of organic matter, and soil seed bank pauperization (Brancalion et al., 2016). In São Félix do Xingu, where the community with the highest deforestation rate in our study is located (the surroundings of Tapirapé-Aquiri

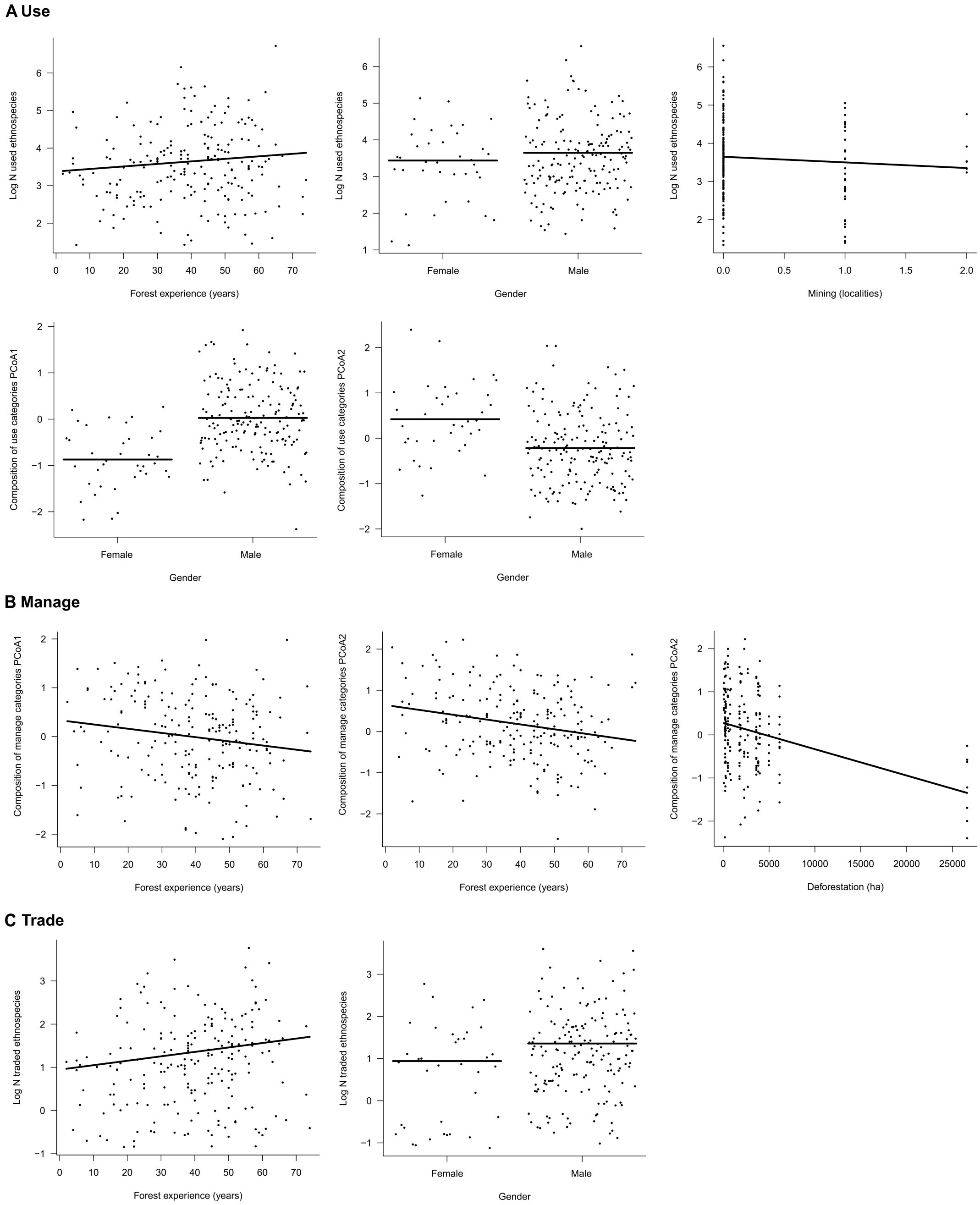

FIGURE 3
Partial residual plots between variables that are statistically significant in linear models: **(A)** used ethnospecies richness, composition of use category—PCoA1 and PCoA2; **(B)** relative abundance of management category—PCoA1 and PCoA2; **(C)** traded ethnospecies richness. Each point represents one individual; lines represent model predictions. The Y axis corresponds to partial residuals, and thus shows the relationship between a given dependent variable and a given predictor while controlling for the effects of remaining predictors in the model.

FLONA), there are several incentives for restoring degraded areas through the implementation of agroforestry systems with cacao (*Theobroma cacao*) (Braga, 2015). Braga (2015) interviewed 16 family farmers in this region and reported that half of them received training to work with these agroforestry systems, and 81% received seedlings from a government agency.

In the lower Tapajós River region, rubber agroforestry has a long tradition, dating back to the end of the 19th and the beginning of the 20th century. However, with the drop in the price of rubber, it fell into disuse. Since the 2000s, projects have been developed in this region (including in the FLONA Tapajós) to encourage the use and increase the productivity of the rubber agroforests using new techniques and enriching the systems with other species (Schroth and da Mota, 2013). These projects included the implementation of local seedling nurseries and the training of residents, knowledgeable of local practices, to be supporting technicians (Schroth and da Mota, 2013). In our study, forest specialists mentioned projects that involve training courses, implantation and maintenance of native seedling nurseries, and planting in deforested areas. They even explained some specific cultivation techniques that they learned in the projects, such as seed scarification or grafting. Within the projects and incentives, the traditional knowledge and practices are integrated with new techniques, improving the planting process, management, extraction of forest products, and promoting forest restoration.

We did not find a significant effect of fires on the components of TEK that we evaluated. Fires have increased in recent years as one of the main complements of deforestation (Escobar, 2019). On the other hand, fire management is probably the most frequent and effective way to alter and enrich forests and other ecosystems with useful plants (Parrotta et al., 2015; Levis et al., 2018). Fire has been used for millennia by the Amazonian peoples to transform landscapes into more productive and safer areas (Clement et al., 2021). Although we assumed that the fires detected were an external environmental threat (due to their extension), they could also represent more intensive fire management or even accidental fires, carried out by traditional people themselves. Thus, although our results did not show a significant fire effect on forest TEK, we cannot discard the possibility that we confounded different fire situations, masking their effect as a threat.

Forest traditional ecological knowledge and environmental threats: Simplifying a complex scenario to look for patterns

The simplification of forest TEK to just a few of its components, such as the number of plant species cited, can limit the conclusions of the study, but allows for general comparisons (Hanazaki et al., 2013). Forest TEK is much more complex than ethnospecies richness and composition of use and management categories we analyzed. Thus, although we found a small effect of mining harming the forest specialist's knowledge of used ethnospecies, we cannot refute the hypothesis that other components of TEK, such as the specialists' cultural beliefs, are compromised by environmental threats.

The threats we analyzed are only a part of the scenario, which is far more complex than our models, because the scenario is affected by the political context. Currently, the millions of people that live in rural landscapes in Amazonia depend, at least partially, on forest resources for their wellbeing, and PAs are often essential to ensure the rights of these people to access, use and manage forest resources (Veríssimo et al., 2011). Since 2015, Brazilian federal policy has dismantled the social-environmental agreements and regulations that local people depend on (Fearnside, 2016). This trend intensified with the "death agenda" of the Bolsonaro government, which actively dismantled government agencies responsible for the PAs' management plans, thus threatening traditional peoples (Ferrante and Fearnside, 2019). Our study suggests that the stocks of TEK (or at least some components of TEK) in Amazonian rural communities, especially in PAs, are resisting environmental threats, but how long traditional peoples can resist increasing political threats is an urgent unanswered question. Since conservation is more about people than biodiversity, answering this question will help predict the future of the Amazonian biome.

Concluding remarks

We documented a great number (N = 795) of used ethnospecies. What local forest specialists know probably reflects what they effectively use, manage and trade. This TEK suggests dependence on forest products for their livelihood, and conserving the forest is crucial for traditional peoples' future. Surprisingly, the environmental threats we analyzed had smaller effects on TEK than personal characteristics. Considering the complexity of TEK and that we only assessed some of its components (knowledge of useful species, uses and management), we cannot refute the hypothesis that environmental threats harm other TEK components, such as cultural beliefs. However, our broad quantitative comparative approach shows that important components of knowledge persist in the face of environmental threats across Brazilian Amazonia. In view of this evidence, we encourage future studies that consider local qualitative approaches allowing more in-depth analyses of TEK, local context and political scenarios. An example would be the study of forest specialists' perceptions of environmental threats. In Amazonia, Indigenous Peoples and local communities have been responsible for maintaining and enriching the standing forest. Our study showed that their knowledge tends to remain solid and resistant in the face of environmental threats and must therefore be recognized as a key element for the elaboration of strategies to change the economic development model that currently dominates the planet and threatens the future of humanity.

Data availability statement

The original contributions presented in this study are included in the article/**Supplementary material**, further inquiries can be directed to the corresponding author.

10.3389/ffgc.2022.1028129

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee for Research with Human Beings of National Institute of Amazonian Research. The participants provided their written informed consent to participate in this study.

Author contributions

RA, CC, JS, CL, MC, and MF: conceptualization. RA, VB, and PP: formal analyses. RA, CL, MC, and MF: investigation. RA, VB, and MF: data curation. RA: writing—original draft preparation. RA, CC, JS, and CL: writing—review and editing. RA, VB, and MF: visualization. CC and JS: supervision. CC: funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding

This research was supported by the Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM)/Fundo Newton (Proc. No. 062.00831/2015), FAPEAM Universal (Proc. No. 062.00148/2020), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) Universal (Proc. Nos. 458210/2014-5 and 435985/2018-3), Programa de Apoio à Pós-Graduação e à Pesquisa Científica e Tecnológica em Desenvolvimento Socioeconômico no Brasil (PGPSE) (Proc. No. 42/2014), and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior–Brasil (CAPES)-PROEX.

Acknowledgments

We thank the residents of the study areas for their kindness and support, especially the forest specialists who participated directly in the research. We thank Helena Pinto Lima, Silvinho Costa da Silva, Marina, Eduardo Kazuo Tamanaha, Emanuella da Costa Oliveira, Patrícia Carvalho Rosa, Maurício André da Silva, Clara Machado, Valdely Kinupp, Victor Lery Caetano-Andrade, Tassia Karina Medeiros, Bianca Weiss Albuquerque, Maria Teresa Fernandez Piedade, Iracenir Andrade dos Santos, Marcos Santana, Flaviane Malaquias Costa, Ana Flávia Francisconi, Lin Chau Ming, Giulia Melilli Serbin, Raquel Tupinamba, Juliana Lins, Danilo Parra, and Priscila Pacheco Carlos for partnership and field support; the staff from Rio Ouro Preto RESEX, Humaitá FLONA, Tefé FLONA, Amanã RDS, Piagaçu-Purus RDS, Uatumã RDS, Tapajós FLONA, Caxiuanã RDS, and Tapirapé-Aquiri FLONA; INPA Santarém, Instituto de Desenvolvimento Sustentável Mamirauá, Museu Paraense Emílio Goeldi, Max Planck Institute, Universidade Federal do Oeste do Pará for field support; the Center for Integrated Studies of Amazonian Biodiversity—CENBAM (INCT supported by CNPq and FAPEAM), and POSGRAD (Resolution No. 008/2021) for logistic support; RA thanks INPA PCI/MCTI for a research fellowship (2014–2017) and FAPEAM for a doctoral scholarship (2018–2021); RA thanks Idea Wild for a GPS and computer, and the Sustainable Use Program of the Humanize Institute for a donation; CC thanks CNPq for a research fellowship (303477/2018-0); CL thanks CNPq and CAPES for post-doctoral fellowships (159440/2018-1, 151231/202-4, and 88887.474568/2020); and two Frontiers reviewers for valuable criticism and suggestions that improved the presentation.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2022.1028129/full#supplementary-material

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