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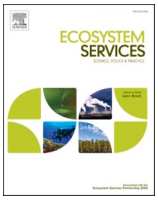

Full Length Article

Ecosystem services and food security: Local perception aligning with demands in the state of Amazonas, Brazil

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ABSTRACT

The Amazon forest is a vital provider of ecosystem services (ES) that support food security in various ways, including through food provision and climate regulation. Despite its rich biodiversity, the region faces striking food insecurity. From an ecosystem-based perspective, this study is primarily based on local perception approach (complemented by secondary data surveys) to capture the interplay between ecological availability and people's perceptions of nature's benefits, allowing the identification and assessment of ES related to food security. We examined these perceptions under the hypothesis that communities facing higher levels of food vulnerability would perceive and prioritize food-related ES differently from less vulnerable ones. The study was conducted in three municipalities representing a gradient of food vulnerability – Manaus (medium), Carauari (medium–high), and Tabatinga (very high), and collected data via semi-structured interviews from a total 216 interviewees of the local population. Based on interview citations of nature's benefits, provisioning services accounted for 59% of all ES mentions. Among the specific services, nineteen ES classes were reported, with Food (from crops and livestock) representing approximately 27% of the total mentions. These populations rely directly on the systems they inhabit, and the perceptions varied according to local demands and food vulnerability levels: as food vulnerability decreases, the diversity of perceived ecosystem benefits expands – moving from immediate, survival-oriented benefits toward broader ecological and cultural values. Our findings suggest that the greater the need for a particular ES, the more its importance was recognized (mentioned). Important food security demands were clarified through this approach, underscoring that conservation strategies that incorporate local ES dynamics are essential to enhance community resilience and food security in the Amazon.

1. Introduction

Human well-being lies along a multidimensional continuum composed of five key, reinforcing components: basic material needs for a good life, health, social cohesion, security, and freedom of choice, all underpinned by ecosystem services (ES) (MA, 2003). Despite this comprehensive framing, ES research has historically emphasized biophysical supply-side assessments (ecosystem properties and functions) while comparatively neglecting demand-side dynamics that reflect human perceptions, values, and socio-cultural dependencies (Boerema et al., 2017; He et al., 2025). Among these demands, food security stands out as a core component of well-being, currently affecting nearly 2 billion people across diverse regions (Hussain et al., 2025). Emerging issues such as climate change, population growth, and geopolitical instability are increasingly shaping the vulnerability of food systems worldwide (Roth and Galyon, 2024; Fróna et al., 2019).

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Food security is a facet of health, and it is ensured when all individuals have permanent access to sufficient food for an active and healthy life; when this does not occur, it falls under food insecurity, which can range from mild to severe (FAO, 2008; Kepple, 2014). To ensure food security, four dimensions must be considered: availability, representing the production and sufficient supply of food; access, including physical and economic accessibility; utilization, such as safe food use and its nutrients; and stability, which refers to supporting the other dimensions in periods of instability, such as adverse environmental conditions (FAO, 2008).

It is well established that biodiversity is crucial for the functioning of ecosystem processes, as high biodiversity can ensure both the quantity and quality of ecosystem services in a given location, thereby supporting the dimensions of food security (Arnold et al., 2011; Cardinale et al., 2012; Harrison et al., 2014; IPBES, 2018; Richardson, 2010). For instance, biodiversity provides a variety of wild foods, contributing to food availability; clean, potable water, which is essential for utilization; raw materials for the sale of handicrafts, thereby enhancing economic access to food; and it maintains climate stability, which is vital for the resilience of food systems (Bommarco et al., 2018; Poppy et al., 2014). In the Amazon region, local communities directly rely on various ES, including the provision of food resources, water, medicinal plants, firewood for cooking, and conditions for agriculture, which are also crucial for the economic, social, and cultural dynamics of the region (Almeida et al., 2023; Ortiz et al., 2013). However, this expected link between high biodiversity and food security does not clearly manifest in the Amazon region, where high biodiversity coexists with low food security indicators.

Many tropical regions worldwide exhibit the worst food security indices (FAO et al., 2023). In Brazil, the northern region is the most nutritionally vulnerable, hosting most of the population facing severe food insecurity in the country (VIGISAN, 2022). The state of Amazonas, Brazil, exhibits a noticeable east–west gradient of low levels of food security (CAISAN – Interministerial Chamber for Food and Nutritional Security, 2016), which can be seen as a paradox, as despite its abundance of biodiversity and nutritionally valuable plants, it presents some of the worst food security statistics in the country (Alencar et al., 2007; Ortiz et al., 2013). This apparent paradox can be related to the complex nature of social-ecological systems (SES) (Levin et al., 2013), where interactions among environmental, social, and economic factors often hinder the achievement of all dimensions of food security.

To better understand the apparent Amazon food paradox, given the complexity of the relationship between ES and food security, we need to consider the three main components of the SES: the social system, the ecological system, and the interactions between them (Pacheco-Romero et al., 2020). Data such as land use and land cover serve as an indicator of ES availability (Deloyde and Mabee, 2023; Tashie and Ringold, 2019). However, it allows us to observe only parts of the landscape functions, and the non-directly observable ones require field observations before extrapolating functions from spatial indicators (Burkhard et al., 2009). A larger scale may not capture the real local situation, so it is important to consider different scales to address ES, including institutional processes that may operate at broader or finer scales (Poppy et al., 2014). It is therefore essential to consider the perceptions of local people, who have a direct understanding of how their needs and actions affect, and are affected by, patterns and processes in ecosystems. This allows us to elucidate aspects of the relationship between social actors and ES that are not immediately apparent in their discourse (Diaz et al., 2011).

Including local perceptions of rural and traditional communities through interviews on local ecological knowledge has proven to be highly relevant for the Amazon region researches, as they identify and evaluate numerous ES due to their daily direct dependence on the land and ecosystem (Almeida et al., 2023; Caballero-Serrano et al., 2017; Santos et al., 2023). Studies on ES perception indicate that individuals' perceptions are often associated with their socio-ecological context and specific needs, with more vulnerable individuals tending to perceive more ES related to their vulnerability issues, while less vulnerable ones recognize services about other benefits (Ahammad et al., 2019; Caballero-Serrano et al., 2017; Diaz et al., 2011). Furthermore, vulnerable communities tend to rely more on these nature benefits for nutritional sustenance, such as wild foods, and indirect benefits like pollination, pest regulation, and disaster risk reduction (Ortiz et al., 2013; Poppy et al., 2014). Unlike urban populations reliant on global markets, rural, traditional and socially vulnerable communities rely directly on natural resources for subsistence, making availability and access to these resources critical (Ortiz et al., 2013).

Here we investigate the relationship between ES and food security in Amazonian communities addressing the demand dimension of ES, a critical gap in ES research (Boerema et al., 2017; He et al., 2025). In doing so, we address the limited understanding of how people experience and articulate the benefits of ecosystems, which is especially critical for assessments intended to inform decision-making (Boerema et al., 2017). We focus directly on the availability and tangentially on the access dimensions of food security and captured people's perceptions integrating three complementary objectives: (i) to identify the general ES locally recognized as important benefits from the environment; (ii) to identify which of those services are related to food security, capturing the subset of ES related to food through local perception; and (iii) to assess how communities perceive the availability of these food-related services. By comparing municipalities along a gradient of nutritional vulnerability, we explore whether more vulnerable communities perceive more food-related ES, while less vulnerable ones recognize a broader range of services associated with other well-being components. Differences in perceived services are expected as perceptions of ES depend on the local socio-ecological context (Ahammad et al., 2019; Caballero-Serrano et al., 2017), and vulnerable individuals tend to rely more on access to food items from forests.

2. Material and methods

2.1. Study area

The Amazonas is the largest state in Brazil in land area and it is part of the largest extractive region in the country, ranking first in the quantity of Brazil nuts (*Bertholletia excelsa*) produced and second in açaí (*Euterpe* spp.), and with 97 % of rural producers in the state considered family farmers (IBGE – Brazilian Institute of Geography and Statistics, 2021; IDAM – Amazonas State Institute for Sustainable Agricultural and Forestry Development, 2019, 2020). Data from the Interministerial Committee on Food and Nutrition Security (CAISAN, 2016) shows an east–west increasing gradient of food insecurity in the state (Fig. S1), reflecting the spatial pattern of malnutrition vulnerability across municipalities (classified as medium, high, or very high). The study was focused on three municipalities (Fig. 1A): Manaus (medium vulnerability), Carauari (high vulnerability) and Tabatinga (very high vulnerability). In addition to capturing these different vulnerability levels, the selected cities and specific communities/neighborhoods were also chosen based on trusted relationships between researchers and the involved communities (Emmel et al., 2007) and the logistical feasibility of field access.

Manaus, the capital of Amazonas and the most populous city in the North of Brazil, has 99.5 % of its population in the urban context (IBGE, 2010) with Sustainable Use and Full Protection protected areas (PAs) in around the urban nucleus. The study was conducted with rural and riverine communities in the PA "Puranga-Conquista Sustainable Development Reserve", specifically in the "São Sebastião" and "Barreirinha" communities (Fig. 1B).

Carauari municipality is one of the main producers of vegetable oils, which have significant economic and market potential, providing an additional alternative source of income for family farmers (IDAM, 2020). The economy is based on fishing, small-scale agriculture, extractivism, oil exploration, and the service sector (IBGE, 2021). Work

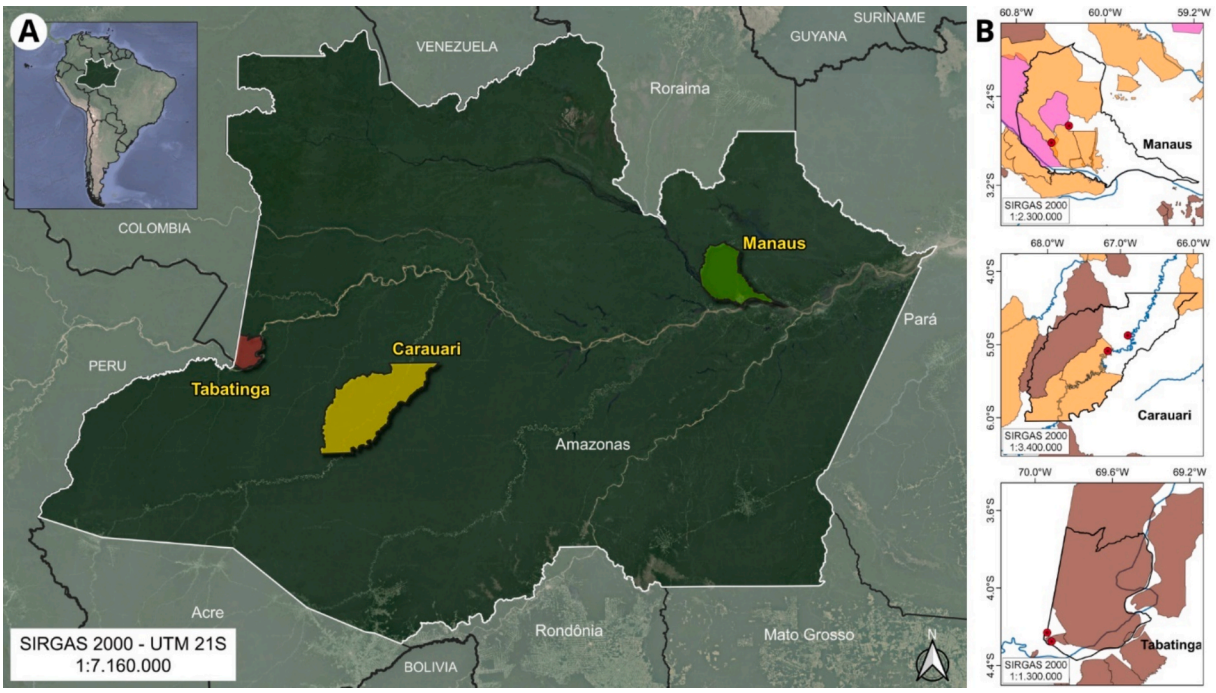

Fig. 1. Location of the studied cities and communities – Map (A) shows the three studied municipalities distributed along the east–west gradient of food insecurity in Amazonas, represented by colors indicating vulnerability levels according to CAISAN (2016): green = medium, yellow = high, red = very high. . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: elaborated by authors. Maps (B) show the protected areas (PAs) within the municipalities of Manaus, Carauari, and Tabatinga, with colors indicating orange for Sustainable Use; pink for Full Protection; brown for Indigenous Lands; and the red dots indicating the interviewed community's localization. The main rivers are represented in blue. Source: ANA (2022); FUNAI (2021); MMA (2020)

points included the riverine community of Nova Esperança, within the "*Médio Juruá* Extractive Reserve", and the "Riozinho" Settlement, under the jurisdiction of INCRA (National Institute of Colonization and Agrarian Reform), in the rural area of the city.

Tabatinga, a municipality characterized by a significant contingent of indigenous peoples and traditional communities (IBGE, 2022),

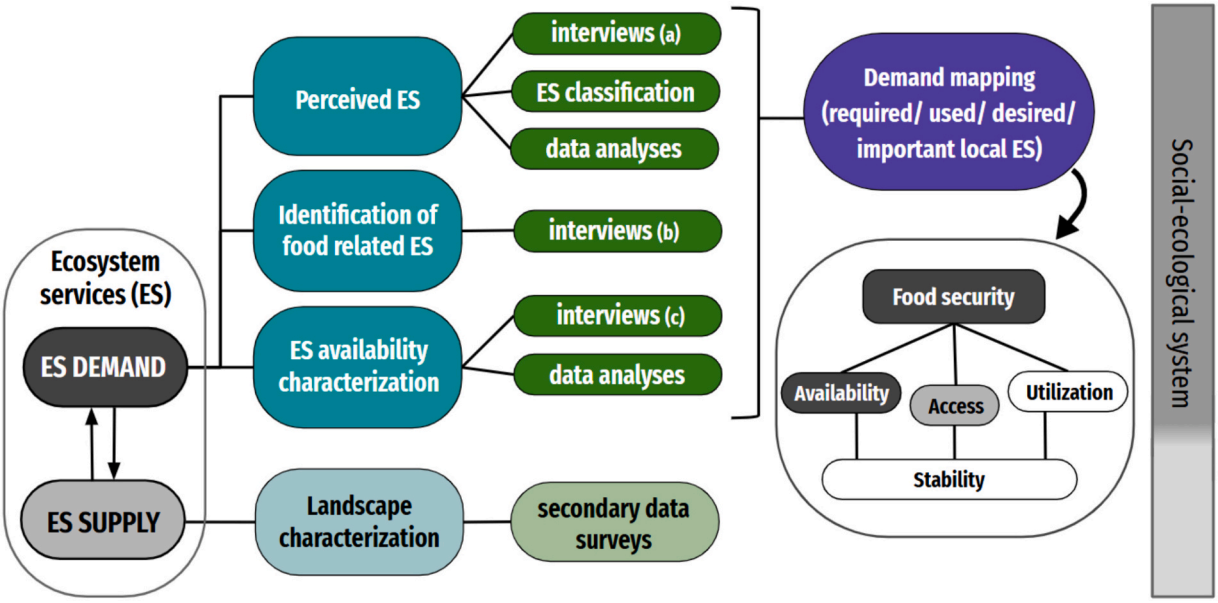

Fig. 2. Conceptual framework – illustrates how the study's theoretical references (gray boxes, with darker tones highlighting the focal areas) informed the methodological developments (colored boxes) and their connection to the Ecosystem Services approach. Turquoise boxes represent the study stages, followed by green boxes indicating methods and tools. Labels "a, b, c" next to interview components refer to the questions asked (described in data collection section). Purple box illustrates the output resulting from these methodologies. The development of this flowchart was based on Boerema et al. (2017) and Levin et al. (2013), addressing linkages among social–ecological systems supply and demand; and Poppy et al. (2014), Bassignana et al. (2025) and Ramirez-Gomez et al. (2015), addressing connections between ES, food security, and local perception-based approaches. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concentrating the highest percentage of rural population among the evaluated municipalities (30.5 %), is ranked among the Brazilian cities with the highest levels of food insecurity (CAISAN, 2016). The economy is marked by commercial fishing and agro-extractivism in the vicinity of the city and rural communities (IBGE, 2021; IDAM, 2020). The present research was conducted at the Tikuna farmers market and the Rural Syndicate Headquarters ("*Sede Sindicato Rural*"), which included residents of indigenous communities, such as Umariaçú I and II (urban perimeter).

2.2. Conceptual framework

We structured an analytical design (Fig. 2) to enable the assessment of ES demand related to food security in Amazonas state, by capturing the ecological scenario as well as the contextual knowledge and lived experiences, linking ecological patterns with perceived human needs – essential elements in understanding complex social–ecological systems (Bassignana et al., 2025). Understanding the dynamics of ES requires recognizing of such both sides: supply and demand, which represent complementary yet distinct aspects of the human–nature relationship (Boerema et al., 2017; He et al., 2025). Essentially, ES supply refers to the ecological capacity of ecosystems to provide goods, functions, and processes that sustain human well-being; whereas ES demand encompasses the amount of goods and services required, used, or desired by society (Burkhard et al., 2014; Villamagna et al., 2013).

In the present study, a specific focus is given on the demand side of ES. Capturing people's perceptions related to the benefits provided by nature and the links with food security represents a key expression of ES demand, as it reflects the benefits that society recognizes and considers important. Perception is understood as a "living memory" that stems from people's multisensory experience with the environment (Ingold and Kurttila, 2000) and the perception approach investigates reality through the subjective perceptions of individuals involved in the studied phenomenon, providing valuable insights for its explanation and understanding (Meredith et al., 1989).

These aspects of ES demand were captured through semi-structured interviews (further described) that explored how residents perceive and interpret ecosystem contributions to food security. Such approach provides a more transparent characterization of ES and a more efficient way to capture community contextual perspectives, compared to census-based or purely narrative/account-based methods (Diaz et al., 2011; Knott et al., 2022), while delivering reliable data on issues particularly relevant to communities, enhancing the reliability of the data (Ramirez-Gomez et al., 2015).

The study was developed under three complementary stages: (1) we conducted a broad identification of ES based on what people recognized as important benefits from the environment; (2) we refined these perceptions by asking participants to relate the identified services to the specific well-being dimension studied, food security, to capture the subset of ES related to food; (3) we examined participants' perceptions regarding the availability of these food-related services, to capture how people perceive access to and sufficiency of the services on which they rely on. In addition, Land Use Land Cover (LULC) data – considered a proxy for ecological properties, a supply measure (Boerema et al., 2017) – were used for a landscape characterization that considered both ecological and cultural features, providing context for the identification and assessment of services (Fig. 2).

To enable transformation of qualitative data from interviewees into quantitative one by using ES framework (MA, 2003), the interviewees' responses were translated into ES classes by cross-referencing established works (Burkhard et al., 2014; Díaz et al., 2018; Wood et al., 2018; Haines-Young and Potschin, 2018 – Table S4) and applying the authors' expertise to reach consensus, particularly in cases requiring further clarification. We consider "ES mentions" as specific references made by respondents to benefits derived from nature (interview protocol provided in Supplementary section S2). Each mention was coded according to its corresponding ES category (e.g., Provisioning, Regulating, Cultural) and class (e.g., Freshwater, Air quality, Recreation). For example, a statement such as "*we collect açaí and other fruits from the forest nearby*" would be classified as a mention of Wild Food, coded under the provisioning category.

While the traditional classification of ES was foundational, we identified a need to expand this framework by integrating additional classes that better reflect the cultural and multidimensional perspectives prevalent in the local Amazonian context. Given the unique nature of the region, many benefits described by the interviewees did not fit neatly into established ES classes, like some regulating or cultural services, but were crucial aspects of local perceptions and values around biodiversity. Therefore, to supplement the ES framework in a way that acknowledges these key contextual nuances, we incorporated two classes aligned with the IPBES framework (Nature's Contributions to People – NCP).

The first, "Habitat and Biodiversity Maintenance" (drawing from the NCP "Habitat creation and maintenance" in Díaz et al. (2018), and adapted following insights from Wood et al. (2018) to better capture the central role of biodiversity), conveys the integral role of plants, forest and biodiversity in people's daily lives, such as general maintenance of life cycles, as expressed by the interviewees. The second class, "Maintenance of Options" (NCP from Díaz et al., 2018), captures concerns related to biodiversity preservation, deforestation, and the desire to safeguard a legacy for future generations. This addition approach complements, rather than replaces, traditional ES classes, ensuring coherence while accommodating regional and cultural specificities, and allowing for a more nuanced understanding of how people relate to nature in the Amazon. Further details on this classification can be found in the Supplementary Material.

We also examined how the people's perception pattern varied among municipalities with different levels of food security, providing a basis for exploring potential links between food vulnerability conditions and the types of services most valued by communities. Lastly, indicators such as perceived scores can serve as an effective way to incorporate local information into an ES assessment, as these scores often reflect a recognized importance – directly corresponding to the demand component (Boerema et al. 2017). Following this rationale, the perceived importance of ES (expressed by ES mentions) and perceived availability of ES (expressed by ES scoring procedure – further described) were analyzed as indicators of ES demand in our study. This component addresses not only the amount of ecosystem benefits required but also the values, cosmologies, and principles that guide what local people consider necessary, scarce, or abundant in their environment (Hicks et al., 2015; Pascual et al., 2017). Therefore, even when people assess the availability of a service (e.g., perceiving it as abundant or scarce), this perception still reflects demand – since their evaluation is shaped by their dependence on, and expectations of, those services.

2.3. Data collection

The primary data was collected via semi-structured interviews with the local population, conducted from July to September 2022. Semi-structured interviews are a qualitative method combining pre-planned questions with the flexibility to explore emerging topics during interaction, enabling the capture of detailed, contextual insights while maintaining minimal structure to ensure data comparability (Bernard, 2006). In this study, the guiding questions were based on a previously structured protocol focused on the research themes, while responses were open-ended, allowing participants to elaborate freely and introduce additional aspects they considered relevant.

The present study is part of a broader research project integrating natural and social sciences, with the semi-structured interview protocol (Supplementary Material – section S2) addressing perceptions of ES, food security and its elements, and climate change (analyzed across different studies). The project was reviewed and approved by the Research Ethics Committee (protocol 5468154). For the purposes of this

research, the main analysis focused on three questions: **a.** "Is there anything in the environment/nature that you consider important for your life, or for the health of your family and friends?"; **b.** "In your opinion, are these elements connected to your food?"; **c.** "Considering the place where you live, would you say these elements are very abundant, abundant, scarce, or very scarce?". The remaining questions from the interview protocol served as analytical support for the discussion presented in this study (see Supplementary S2 section S2) and were referenced in the Results section when relevant. Interviews were conducted by various researchers (some authors and research technicians), followed a non-technical language protocol and could be recorded and/or transcribed, with Portuguese as the primary language used (except for some interviews with indigenous people in Tabatinga, which included simultaneous Portuguese-Tikuna translation).

Interviews were carried out in selected rural and riverine communities of Manaus, Carauari, and Tabatinga (as described in the Study area section), with local smallholders (rural producers/agricultural family members) and traditional residents, hereafter referred to as 'locals'. This sample was selected because such communities represent populations more vulnerable to food insecurity in the Amazonian context (Torres-Vitolas et al., 2019) and that maintain a direct relationship with local ecosystems (Lira and Chaves, 2016), which enables a more accurate understanding of the issues investigated., The selection of this particular group of interviewees (n = 216) was based on convenience sampling, a non-probability form of sampling, which describes the data collection process from a research population that is effortlessly reachable to the researcher (Rahi, 2017). Conducting a qualitative study frequently involves the use of convenience sampling in the social sciences, where researchers have ready access to existing target populations (Penn et al., 2023).

Regarding the logistics of fieldwork, flexibility was essential, as interviews were typically conducted at participants' homes and lasted approximately 20 min to one hour, depending on the flow of the conversation (see Supplementary section S1 for details). The timing and scheduling of interviews were adjusted to the availability of individuals in each community, aiming to include as many participants as possible in order to obtain a reliable and coherent understanding of the perceptions within each location. In total, 216 interviews were conducted across five communities distributed among the three municipalities: Manaus (n = 56), Carauari (n = 89), and Tabatinga (n = 71). All subsequent analyses accounted for variations in the number of interviews conducted in each municipality.

Additionally, a secondary data survey was conducted to provide contextual information and support a broader understanding of the study setting, as well as better interpretation and discussion of the potential drivers for results patterns (Bassignana et al., 2025; Burkhard et al., 2012). A socio-environmental scenario of the studied municipalities was investigated, using Pacheco-Romero et al. (2020) as a reference for indicators. These environmental and socio-economic data were obtained from the Brazilian Institute of Geography and Statistics (IBGE, 2018, 2008, 2010, 2021, 2022) and from CAISAN (2016), which provided information on the status of food security.

Considering Land Use and Land Cover (LULC) as an indicator of ES availability (Boerema et al., 2017), a survey of LULC classes was carried out for the areas where interviews were conducted, using QGIS free software (3.16 version – (QGIS, 2009) and MapBiomas data (Collection 8, spanning from 1985 to 2022 – Mapbiomas, 2022). LULC data was used not only to provide contextual support but also to offer insights into the potential ES provided by ecosystems and their availability, since ES provision is inherently linked to biophysical characteristics and their variation across space and time (Burkhard et al., 2012). Accordingly, it is expected that certain types of LULC exhibit higher potential of ES provision, while others may have lower capacities (Burkhard et al., 2009). In addition, LULC data can also provide indicators of ES supply, representing the ecological context and potential availability of natural elements within the studied area (Deloyde and Mabee, 2023; Tashie and Ringold, 2019).

2.4. Data analysis

The ecosystem services were classified based on the local communities' perceptions of nature's benefits, gathered through interviews, also reinforced or validated using LULC data to cross-reference available services in the area. The data consisted of qualitative interview transcripts and quantitative LULC information, which were analyzed in an integrated manner to connect local perceptions with ecological patterns. Analysis of patterns related to the representation of vulnerability and the characteristics of individual communities was conducted, along with data on resource availability (abundance/demand analysis from LULC data and interviewees perception).

Firstly, the data collected through interviews were systematically processed, (such as audio recordings thoroughly transcribed and organized in spreadsheets), to ensure methodological consistency in coding. The next step involved conducting a thematic analysis as part of a content analysis methodology (Biggs et al., 2021). This approach aims to identify themes, also known as patterns, in the dataset, involving three fundamental stages: (a) an initial, holistic reading of the text (e.g. interviewees' answers); (b) analysis and fragmentation of the text by identifying relevant subsections (themes aligned with the research objectives), and coding the subsections by attributing ES classifications based on participants' perceptions; and (c) elaboration and refinement of the coding/classification system as more texts (e.g. additional answers with new perceptions) appeared throughout the process (Biggs et al., 2021).

As previously described in the Conceptual Framework section, this process involved translating narratives into specific established classifications, such as ecosystem services classes (Bauer et al., 2022; Evangelista et al., 2024), using a triangulation approach to enhance data reliability and validity (Drumond et al., 2009). To operationalize this step, the ES mentions (from "question a") were organized in binary matrices (1/0), indicating the presence or absence of each classified service in respondents' statements. From this dataset, we calculated the overall frequency of each ES mentioned across respondents and municipalities, providing a quantitative overview of the most frequently perceived local benefits. In addition to the general ES classification, we analyzed the interview responses about whether the mentioned benefits were related to their food security ("question b"), therefore focusing specifically on ES related to food in some way. These responses were also encoded as binary data, with "1" representing the cases where a connection between the cited benefit and food security was explicitly mentioned. The relative frequency of each ES in this subset was then calculated considering all mentions linked to food as 100 %, allowing the comparison of how strongly each service was perceived as contributing to food security.

Variance analyses were performed to identify significant differences in the ES mentions across localities, using multiple logistic regression with a categorical variable, along with the prediction of probabilities of mentioning each service by locality (through reader, haven and ggplot2 packages in the R programming environment) (Cooper, 2017; R Core Team, 2022; Wickham, 2016; Wickham et al., 2023b); as other analyses were not compatible with the nature of the data (binary, categorical, with unbalanced numbers of interviews per city) or incomplete with the outputs of interest. Subsequently, the relationship of those benefits with personal/local food in the opinion of the respondents, as well as the locals' favorite foods, the main crops planted, and the types of foods that are part of the daily diet of the interviewees were added to the analysis.

While the previous steps elucidated analyses regarding the quantification of ES perception patterns, the following step aimed to assess their ecological availability in the study areas. The availability characterization built upon the previous analytical steps and incorporated both spatial and perceptual dimensions. Interview data captured local perceptions on the availability characterization ("question c"). Each

interviewee was asked to rate the benefits they mentioned (classified into ES) on a "Likert scale" ranging from 1 (very scarce) to 4 (very abundant) (Joshi et al., 2015), providing an overview of supply and demand from their perspective. Some interviewees provided an overall score for the identified ES, while others rated each mentioned benefit individually.

Variance analyses were conducted using the Kruskal-Wallis and Dunn tests to verify significant differences in assigning ratings to services in each municipality (through dplyr, rstatix, and ggplot2 packages in the R programming environment) (Kassambara, 2023; R Core Team, 2022; Wickham, 2016; Wickham et al., 2023a). The evaluated services were the top three related to food according to local perception and presented a significant p-value in the frequency analysis of mentions per city.

Additionally, the municipalities' LULC data, incorporated to support the identification and characterization of services, were locally analyzed through the establishment of an influence zone: 6 km buffer around the interviewed communities (Table S2 provides the rationale), referred to as 'sites' throughout the study. Through QGIS tools (QGIS, 2009), the area in square kilometers and the percentage of each LULC class were calculated. Since respondents described the perceived importance/ abundance/ scarcity of natural elements essential to their livelihoods, it was enabled linking ES identified to the LULC classes in each municipality, based on the main environments where these benefits were reported to occur (e.g., forest areas, rivers, or urban areas).

Therefore, these steps allowed us to quantify, for each municipality, how frequently each ES was perceived as a local benefit and how frequently it was linked to food security in people's accounts. They also enabled us to explore analyses such as comparing frequencies across municipalities with different levels of food vulnerability and cross-referencing them with LULC-based availability indicators at both regional and local scales, forming the basis of the analytical flow.

3. Results

3.1. Perceived ecosystem services

Based on interviewees' perceptions, we identified a broad range of ES categorized into: provisioning (six services), regulating (six services), cultural services (five services), and NCP (two) (Fig. 3). As in other studies on ES perception in the Amazon region (e.g., Almeida et al., 2023; Caballero-Serrano et al., 2017; Santos et al., 2023), this diverse set of classes reinforces how people perceive the benefits differently depending on their context (Ramirez-Gomez et al., 2015).

In general, from the ES mentions data, the citation frequencies were highest for the provisioning category (59 % of ES mentions belong to this category), followed by NCP category (13.8 %), regulation (13.6 %), cultural (10.4 %), and "others" (3.2 %) (Fig. S2). The Food (Crops/ Livestock) service was the most frequently mentioned, both in relation to the overall dataset (~27 % of all ES mentions – Table S4), and as the

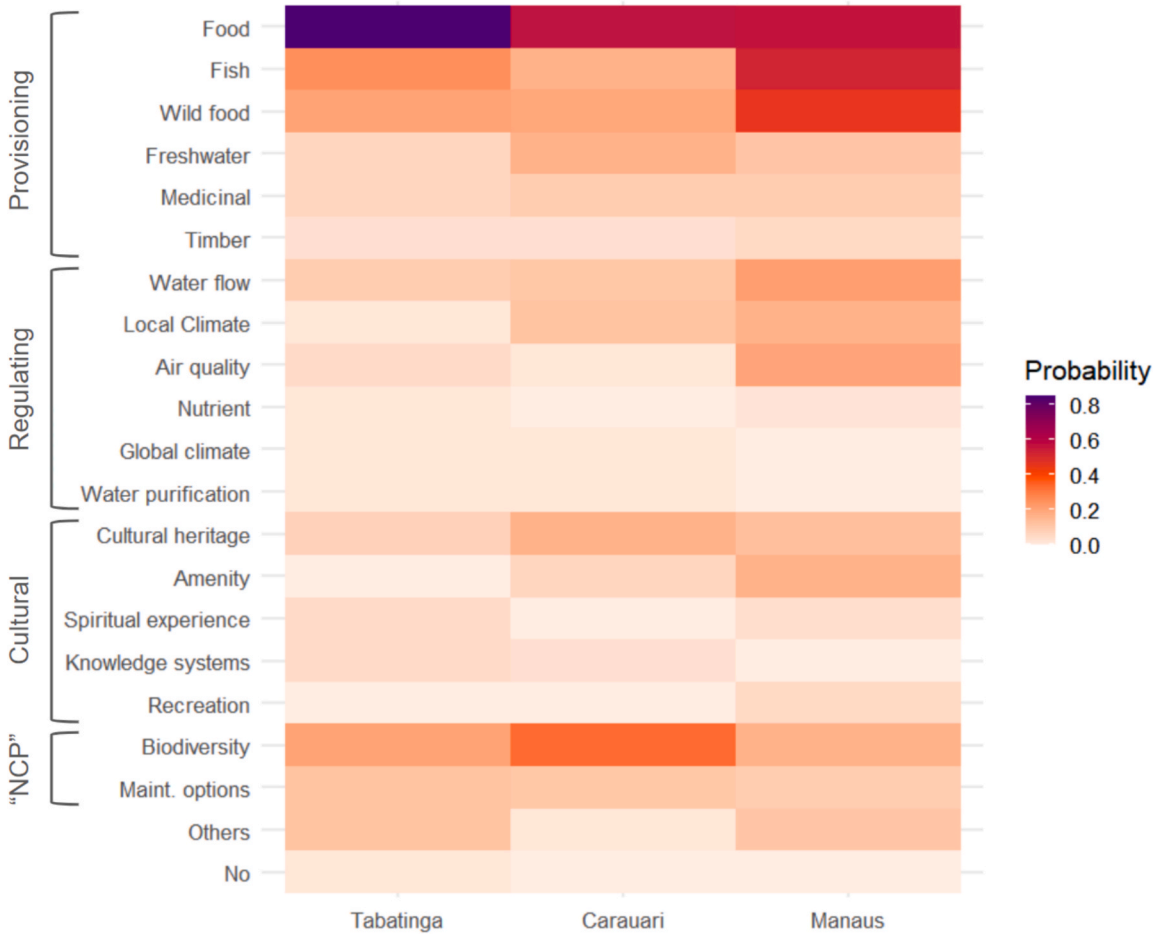

Fig. 3. Probabilities of ES mention by city – Heatmap representing the probability analysis of ES mention in each of the studied cities (Manaus n = 56, Carauari n = 89, Tabatinga n = 71), grouping the mentioned ecosystem services and benefits into categories. Within each category, the ES list is arranged from the highest to the lowest probability of mention across municipalities. Beyond the identified services, we also added two classes/categories: one named "Others", which refers to evasive answers or benefits mentioned by locals which are not listed as an official ES by classification systems; and the other named "No", to include responses from individuals who claimed not to recognize any nature-related benefits (only one response). See the abbreviation of ES names in Table S4.

top-cited service in each of the three municipalities. In terms of the relevance of those ES for food security, the interviewees associated Food (Crops/Livestock), Fish, Wild food, Habitat and Biodiversity Maintenance and Water flow services as the most important ES (Fig. 4), individually described below.

Food (Crops/ Livestock) ES, referred to as 'Food' throughout the study, is distinct from wild food sources or fishery services, since specifically encompasses cultivated crops and livestock – including responses about planting (e.g. swiddens, fruit trees, and cultivating vegetable gardens) and raising animals. Subsequently, Fishery (12 % of the mentions) mainly includes fishing for species such as tambaqui, pirarucu, and tucunaré. The Wild food service (11 %) encompasses hunting, primarily of mammals (e.g. tapir, peccary, agouti) and plant extraction (such as açaí, tucumã, buriti), with species details specified in Table S7. These services represented either for subsistence or commercial purposes. Lastly, the Habitat and Biodiversity Maintenance (~10 %) are perceived by locals as the legacy of plants, forest and biodiversity in maintenance of life cycles; and Water flow (5.3 %), perceived as balanced season precipitation, water availability in the lakes and rivers, and water flow as a means of transport (Table S4).

Regarding differences among the cities (Fig. 3, Table S8), Tabatinga (the most nutritionally vulnerable municipality) has the highest probability of perceiving the Food (Crops/Livestock) service (~85 %, $p < 0.0006$). Respondents from Carauari perceived more Freshwater (~17 %, $p < 0.04$) and Habitat and Biodiversity Maintenance (~33 %, $p < 0.03$) than the other cities. In Manaus, Fish (~53 %, $p < 0.002$) and Wild Food (~45 %, $p < 0.002$) were more recognized by locals than in Tabatinga and Carauari. We can also observe that Manaus was the region where people mentioned more regulating and cultural services when compared to the other municipalities (Fig. 3).

Delving further into other relevant information captured in interviews, although these food-related ES contribute primarily to daily nutrition, locals reported that a large portion of their daily food is actually purchased (interview protocol question 17 – Supplementary section S2). Most individuals in all municipalities engage in food production in small areas, such as their own home gardens and swidden agriculture, usually dedicating their lives to tending these swiddens – "*is our economy, for the people here; 2 % have fixed jobs, the majority is the 'roça'. It's tradition*", as one Tabatinga local expressed. This production includes native plant foods, such as manioc (also known as cassava), açaí, and banana, as well as non-native crops like maize and mango, along with animal-based proteins from poultry, pork, and cattle – also, these commonly cultivated crops align closely with the plant-based foods frequently mentioned as part of the interviewees' daily diet (interview protocol question 14 – Supplementary section S2). People also engage in extractivism in the surrounding forests, mainly for food items (hunting being widely mentioned) – highlighting the Wild Food ES and demonstrating the importance of forest dominant coverage (Fig. 6). Açaí serves as an example of a food item cited by locals both as cultivated by them and extracted from the forest.

Furthermore, regarding the variety of foods consumed across the three cities, the most frequently mentioned favorite food was fish, followed by chicken in Tabatinga, wild food (hunting) in Manaus, and açaí in Carauari. Fish as the most cited favorite across all cities, is corroborating with its ingrained culture in the state of Amazonas as a whole (IDAM, 2020) – as evidenced by statements like "*I grew up eating fish*" (local of Manaus). As well as açaí (Borba, 2019), the second most favorite food in Carauari, stood out as a cultural element in the local diet, with locals expressing "*açaí is our culture here, after lunch or dinner, you have açaí!*". In Tabatinga, there was a greater variety of foods mentioned, (37 different types – Fig. S3), which could be attributed to a broader diversity in food culture due to a larger indigenous population, valuing a greater quantity and other types of food (Cassino et al., 2021).

3.2. Ecosystem services availability

In the examination of availability/abundance ratings concerning the three primary ES linked to food, as perceived by the local population, noteworthy variations among the cities have surfaced (Food: $p < 0.001$, Fish: $p < 0.05$, Wild food: $p < 0.015$).

While Food was the most frequently perceived ES in Tabatinga (Fig. 3), locals consistently assigned lower availability ratings for this service, with a concentration of scores primarily in 2 and 3 (the main difference being between Tabatinga – Carauari, p-value = 0.00000647).

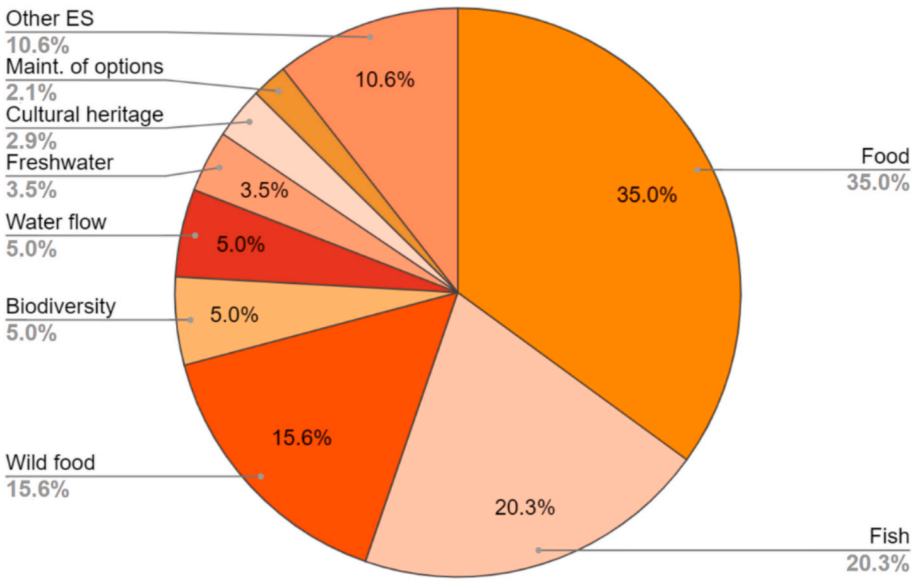

Fig. 4. Local perception of ES related to food – chart illustrating the proportion of mentions for each ES identified as contributing to food security according to interviewees. Percentages were calculated based on the total number of mentions of ES explicitly linked to food across all respondents (i.e., 100% corresponds to all citations where interviewees associated an ES with food or food security). It is important to emphasize that the ES "Food" represents crops and livestock – see the abbreviation of ES names in Table S4. The "Other ES" group includes all remaining services, each accounting for less than 1.5% of food-related mentions (biochemicals and medicine, local climate regulation, air quality regulation, timber, landscape aesthetics and inspiration, global climate regulation, knowledge systems, religious and spiritual experiences, nutrient regulation, water purification, and recreation and tourism).

In contrast, in Manaus and Carauari, the ratings were more evenly distributed around 3 and 4 (Fig. 5). Ratings for the "Wild food" service followed a similar trend, where Tabatinga exhibited lower scores, while Manaus and Carauari tended to cluster around 3 and 4 (main difference Tabatinga − Carauari, p-value = 0.0178). However, for the "Fish" service, a distinctive pattern emerged, with Manaus providing the lowest ratings (main difference Manaus − Carauari, p-value = 0.0350).

Interviews revealed that discussions regarding hunting and fishing often revolved around scarcity, noting fewer animals in the forests and difficulties in fishing. At the same time, "very abundant" typically referred to plants, forests, and clean air. Many interviewees additionally commented on possible reasons for the scarcity of benefits, including several factors: seasonality ("*it is abundant but only during each food's season*", "*there are periods for ingá* [*Inga* spp. fruit], *there are periods for abiu* [*Pouteria* spp. fruit]"); climate/environmental change ("*it is abundant, but there used to be more*"); and even theft of produce (exclusively in Tabatinga). In Carauari municipality, people talked about the "hunger calendar", describing that there is no food to eat in October, November, and December (the beginning of the flood season). It's important to note that this study did not measure seasonal aspects, such as collecting data at different periods, but rather relied on common reports across the three cities, indicating its relevance.

In total, five standard LULC classes were identified in the influence zones (sites): Forest, Water, Pasture, Non-Forest Natural Formation, and Urban Area (Fig. 6). Although crop production is known to occur in the region, they were likely not captured as a distinct class due to the limited spatial resolution or classification of the dataset for small-scale agricultural areas (e.g., Souza et al., 2019). Across all studied sites, forest stands out as the predominant LULC class, however, a nuanced examination reveals distinctive patterns for each municipality.

In Manaus sites, water coverage emerges as a notable feature, registering the highest percentage among the three areas (Fig. 6C, Table S3), despite being the municipality where fish scarcity was most frequently reported in interviews. Carauari, on the other hand, exhibits the highest pasture coverage and the lowest water coverage (Fig. 5B). Tabatinga has the highest urban area rate, pasture also holds relevance in this area and the municipality exhibits the second-highest water coverage (Fig. 5A). However, the local population expressed concerns in interviews ("*Water is being polluted, no longer suitable for drinking, not useful for anything. In the past (…) we used this water for everything. It was very very clean*" and "*The water quality decreased a lot due to deforestation. Everything got polluted*").

Locals also emphasized the cultural importance of streams where children fish by hand-catching fish, even with absence of security for fishing, highlighting social and environmental concerns related to water coverage. The three municipalities exhibit marked socio-environmental contrasts (Table S1), with Manaus showing higher urbanization, better access to water, education, and employment, and moderate food vulnerability, while Tabatinga and Carauari present predominantly rural populations, lower socioeconomic indicators, and higher levels of food and nutritional insecurity, despite maintaining greater natural vegetation cover and lower land use intensity. A summary of key results for each municipality is provided in supplementary material (Table S8).

4. Discussion

We find that local perceptions of ecosystem services, particularly those related to food, are shaped by a complex interplay of contextual factors (such as environmental dynamics, social vulnerability, and culture), marking the differences between the patterns we found. These perceptions mirror the ecological surroundings (Garau et al., 2023) and express the immediate needs and experiences of scarcity of local communities (Amin et al., 2015) which form access to and reliance on natural resources (Casado-Arzuaga et al., 2013; Ramirez-Gomez et al., 2015). Therefore, people's perceptions offer valuable insights into both the ecological availability and demand dimensions of ecosystem services (Elwell et al., 2018; Mehring et al., 2017), which we discussed in the following sections.

4.1. Ecosystem services perception

A comparing analysis across the studied municipalities reveals a consistent association linking vulnerability and ES perception. Tabatinga, characterized by the highest levels of food insecurity and urban land cover, exhibited the lowest ratings for food-related ES, and the highest likelihood of perceiving them. This pattern suggests that perceptions are related to demand and conditioned by unmet needs and vulnerability.

Carauari, with the highest pasture and lowest water coverage, exhibited a greater probability of perceiving habitat/biodiversity maintenance and freshwater services. This supports the hypothesis that resource scarcity enhances awareness of ecological functions (Almeida et al., 2023). In Manaus, despite high water availability, fish-related services were perceived as threatened, receiving the lowest ratings among the three cities. Santos et al. (2023) also observed that Eastern Amazon farmers perceive fishing as the most important but also the most threatened ES.

When examined along with the food insecurity gradient (CAISAN, 2016), perception patterns become clearer. In the most vulnerable context evaluated (Tabatinga), only provisioning services (food) were significantly mentioned. In Carauari (moderate vulnerability), freshwater and habitat/biodiversity maintenance services stood out. In contrast, Manaus (the least vulnerable) recognized a broader range of ES, including provisioning, regulating, and cultural services. Caballero-Serrano et al. (2017) observed a similar pattern in the Ecuadorian Amazon where groups with higher socioeconomic status tended to

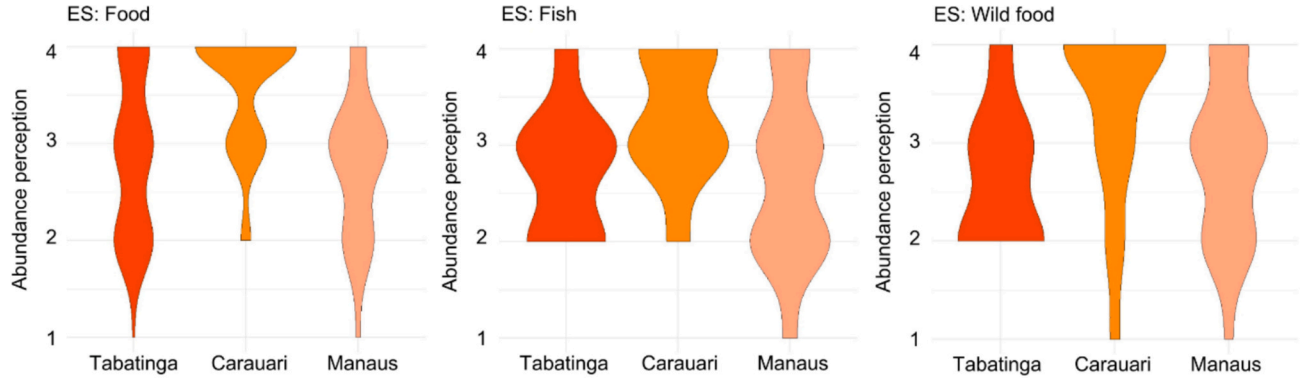

Fig. 5. Availability of ES related to food by local perception − Violin plot analysis to visualize the distribution of scores assigned by locals to the abundance of the ES most related to food security (1 = very scarce, 2 = scarce, 3 = abundant, 4 = very abundant).

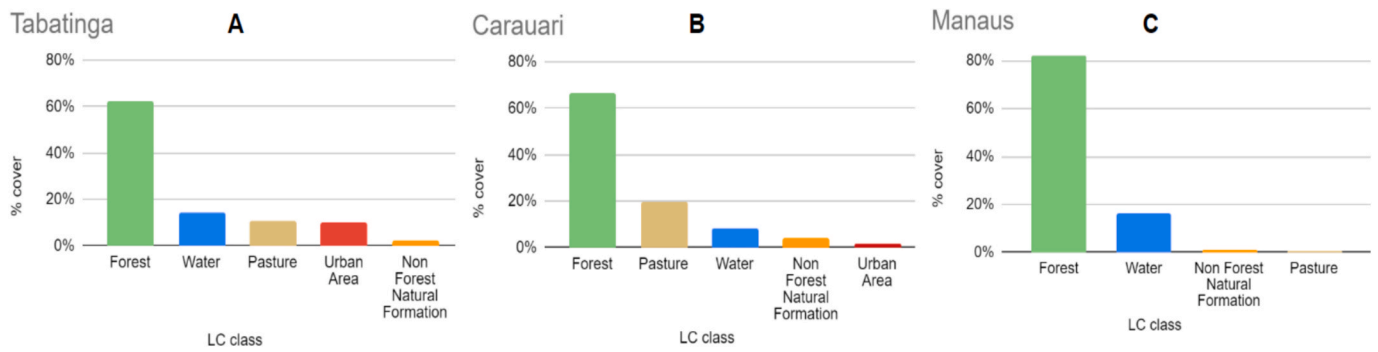

Fig. 6. LULC survey – Survey of land use/ land cover (LULC), by percentage of LULC classes, in the areas where interviews were conducted (A, B and C).

recognize a wider array of cultural and regulatory services. In contrast, most vulnerable ones emphasized provisioning services closely tied to subsistence needs and reported fewer ES overall (Caballero-Serrano et al. 2017). These findings suggest that as vulnerability decreases, the diversity of perceived ecosystem benefits expands – moving from immediate, survival-oriented benefits toward broader ecological and cultural values.

While perceptions are not solely driven by material necessity (Garau et al., 2023; Casado-Arzuaga et al., 2013), our findings underscore a strong link between livelihood vulnerability and how people interpret nature's contributions. Specifically, when individuals perceive a decline or scarcity of food-related services, such perceptions may act as social–ecological indicators of emerging threats, reflecting contexts in which the capacity to obtain food from nature is already compromised.

These insights reinforce the importance of integrating socio-ecological contexts into ecosystem service assessments and food security strategies (Diaz et al., 2011; Haines-Young and Potschin, 2010; Ramirez-Gomez et al., 2015). Recognizing this diagnostic potential of local perception is therefore essential for designing locally grounded strategies that enhance food security and strengthen human–nature relationships in vulnerable regions. Incorporating such knowledge into policy and planning enhances the effectiveness and equity of interventions aimed at promoting sustainable food systems and resilience in vulnerable populations.

4.2. Understanding influencing elements on food availability and accessibility

Despite local differences, all studied localities display some degree of food insecurity and ES mention were predominantly of the primary food-related ES and of provisioning services. However, the provision and stability of such services depend on multiple interacting factors that can often be detected through local perceptions.

Biodiversity plays a pivotal role in maintaining food security, particularly in regions where markets and infrastructure access are limited (such as rural and riverine areas) (Dannenberg et al., 2024). In these contexts, wild species and resources often serve as a safety net during periods of scarcity, providing essential nutritional and economic support (Dannenberg et al., 2024). Empirical evidence from interviews revealed similar insights: wild foods and biodiversity underpin not only household nutrition but also local economies through the sale of products supported by biodiversity which in turn facilitate the acquisition of complementary food items.

Beyond the expected emphasis on provisioning ES, respondents also highlighted the importance on water flow and habitat/biodiversity maintenance services. This suggests a nuanced understanding of the ecological foundations that support food-related benefits. In research linking ES and food security, the most analyzed ES in case studies were also related to food, water and climate regulation, highlighting the importance of provisioning and regulation ES in ensuring the resilience of agricultural communities and food security (Bommarco et al., 2018; Cruz-Garcia et al., 2016; Poppy et al., 2014).

It is important to emphasize that the persistence of traditional communities is intrinsically tied to the integrity of surrounding ecosystems (Levis et al., 2024). The vulnerability of these communities threatens culturally important species, as there is a vital interdependence between cultural practices and biodiversity preservation (Levis et al., 2024; Reyes-García et al., 2023) (see Supplementary Section S3 for an expanded discussion on the cultural, economic, and ecological significance of food-related ES in the studied communities).

Yet, the Amazonian context and the forest cover as the dominant LULC in the studied sites emphasize the mentioned paradox: a region known for abundant biodiversity, but whose population suffers from hunger (CAISAN, 2016). Human-modified landscapes, especially urban areas, tend to exhibit reduced capacity or strong trade-offs in providing ES (Burkhard et al., 2009; Ekka et al., 2020; Gómez-Creutzberg et al., 2019). In Tabatinga, for example, urban area represent the highest rate among the three municipalities sites, but the second-highest water coverage, showcasing a blend of urban and natural landscapes. However, reported concerns by locals, along with studies in the surroundings, reveal degradation of water quality in the region, possibly resulting from urban waste disposal, effluent discharge, and the impacts of deforestation, issues that lead to socioeconomic and environmental impacts on local communities (Bezarra and De Souza, 2021; Oliveira et al., 2023).

Changes in land use and cover, as well as other environmental changes, compromise ecological integrity and, consequently, the ability of ecosystems to sustain essential services such as food production, freshwater supply, and climate regulation (Burkhard et al., 2012; Flores et al., 2024; Lambin and Geist, 2006). Although it is important to note that forest cover remains predominant across all study locations, local concerns about resource quality, seasonality, and environmental change highlight how ES provision fluctuates over time. Tregidgo et al. (2020) provide empirical evidence of seasonal crashes in wildlife catch rates and food insecurity, showing that during the high-water season, fish catch rates drop significantly and food insecurity worsens – which can result in concurrent declines in food security during certain periods. Thus, it underscores the importance of stable access to food and the misconception that resources are consistently abundant over time or that "a region with predominant forest cover" is sufficient information.

The apparent paradox of high biodiversity but low food security in the region can elucidate other global scenarios, where regional ecological richness coexists with several factors undermining food acquisition – such as access to financial resources (Bezerra, 2022), local availability of resources (Ortiz et al., 2013), resource quality (Oliveira et al., 2023), and seasonal variation (Tregidgo et al., 2020). Thus, even though our investigation primarily focused on the food security dimensions of availability and access, it is essential to recognize the dynamics of ecosystems and the impact of these factors on food security, challenging the assumption of a stable food supply. Failure to account for such

variability can lead to misguided environmental and social policies, that assume a consistent food supply (stability) in regions abundant in primary resources.

The interdependence between biodiversity and food production suggests that it is indeed possible to tackle both food insecurity and biodiversity loss through integrated, locally adapted management approaches (Chappell and Lavalle, 2011). Promoting diversified agroecological systems, restoring degraded landscapes, and valuing local ecological knowledge can thus generate synergistic outcomes—enhancing the resilience of food systems while sustaining the ecological foundations on which they depend.

4.3. Future directions

This study contributes to an underexplored yet highly relevant topic by examining how diverse ES contribute to local food security and emphasizing the importance of linking ES and food security through an integrated social–ecological perspective (Garau et al., 2023). By analyzing how local perceptions of ES relate to different levels of nutritional vulnerability and resource availability, our results highlight the diagnostic value of people's experiences for understanding ecosystem dynamics and their implications for well-being. Local perceptions can help reveal processes that remain invisible in large-scale or aggregated datasets, identifying potential hotspots of vulnerability and demand before they escalate into more severe environmental or social crises.

At the local and regional scales, our findings emphasize the need to give greater attention to food-related ES as critical components of food security and human well-being. Understanding these relationships is particularly important in regions where livelihoods are closely tied to natural resources, and where the provision and perception of nature's benefits can directly affect food access and well-being. Defining priorities based on evidence can help maximize the impact of limited resources available for environmental interventions (Scherer et al., 2020). It is equally important to account for ecosystem dynamics, as the provision and stability of these services are influenced by ecological processes, seasonality, and climate variability. Policies that align ecological goals with social needs are essential to advance socioecological justice in Amazonian territories and comparable regions.

Future research could focus on mapping the specific environmental drivers affecting food security, investigating how environmental and climate changes are driving the perceived declines in ecosystem service availability, access, and stability. Such efforts would help elucidate the mechanisms linking ecological variability to food insecurity, underlying mechanisms to refine our understanding of environmental-human well-being relationships and offering insights to anticipate and mitigate emerging risks.

At a broader scale, the insights derived from this study contribute to global debates on including people's perceptions in food security assessments, as perceptions may serve as early signals of social-ecological vulnerability, especially in contexts where quantitative data are scarce. Focusing solely on ecosystem service supply may obscure the true levels of demand and vulnerability experienced by local populations (Yahdjian et al., 2015).

Ultimately, our findings support the view that biodiversity protection and food security are not mutually exclusive goals but mutually reinforcing processes when managed through integrated, place-based approaches. Future research and policy efforts should therefore focus on developing context-specific agroecological strategies that sustain both ecosystem integrity and human well-being, strengthening the adaptive capacity of communities to face environmental and social change.

5. Conclusion

From the different communities we studied in this Amazonas region, we have shown that communities more vulnerable to food insecurity tend to perceive lower availability of food-related ES, as well as the perception of these services varies according to people's demands, vulnerabilities, and their close dependence on local ecosystems. Moreover, we have outlined that more nutritionally vulnerable populations tend to prioritize food-related ES, while less vulnerable groups perceive a broader range of benefits. These findings emphasize the relevance of integrating local perceptions into ES and food security assessments, as they capture key social dimensions that biophysical evaluations or general datasets alone cannot address.

By prioritizing ES demand and local perceptions, this study helps bridge the gap between ecological assessments and the social realities that determine the relevance and success of ecosystem-based policies. Our study gives argumentative support for more integrative approaches connecting local perceptions, ecosystem services, and food security – ultimately contributing to more informed and socially attuned conservation and restoration policies. We conclude that understanding local dynamics of ES availability is crucial for designing effective interventions, since the provision of one service often depends on the proper flow of others.

CRediT authorship contribution statement

Ana Luisa de Carvalho Cruz: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **David M. Lapola:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Moara Almeida Canova:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Tiago da Silva Jacaúna:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Júlia Menin:** Writing – review & editing, Data curation. **Marko Monteiro:** Writing – review & editing. **Giulia Melilli Serbin:** Writing – review & editing. **Maíra C.G. Padgurschi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101807.

Data availability

Data will be made available on request.

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