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Research article

Local ecological knowledge and perception as a strategy in the management of ecosystem services

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ABSTRACT

In designing and implementing initiatives to conserve biodiversity and ensure the flow of ecosystem services, it is crucial to understand the perspectives of communities living near protected areas. Improving conservation efforts may depend on analyzing socio-ecological factors and their impact on Local Ecological Knowledge (LEK) and perceptions of ecosystem services. We employed participatory methodologies with 80 farmers from agrarian settlements adjacent to protected areas in the Cerrado biome, Brazil, we quantified LEK and assessed perceptions of ecosystem services using an adaptation of the Q-methodology. We collected data on thirteen socio-ecological variables, including age, gender, farm size, education, engagement with conservation initiatives, and interactions with protected areas and Legal Reserves. Using artificial intelligence in a Random Forest (RF) modelling approach, we identified the most influential variables on LEK and perceptions. Our findings demonstrate that engagement in nature conservation and restoration initiatives, along with the use of native areas (protected and managed areas) significantly influence LEK levels within the farmers' communities. Farmers with full participation, from conception to implementation and evaluation of the initiatives, had a significantly higher LEK level (28.5 ± 13.0) compared to farmers without participation in those initiatives (11.4 ± 5.9). Farmers who used the cerrado for leisure and education (28.2 ± 21.2) had significantly higher LEK levels compared to farmers who do not attend or use the cerrado areas (13.5 ± 8.9) and those using areas of native vegetation for cattle raising (12.8 ± 6.8). These results highlight that, in addition to farmers' participation in conservation and restoration initiatives, the sustainable use of natural areas is fundamental to strengthen their local knowledge of ecosystem functioning. Furthermore, we found that the type of agroecosystem present on farms strongly? shapes farmers' perceptions of ecosystem services. Farmers perceive different ecosystem services depending on land use, indicating the need for tailored interventions for the planning and management of conservation areas. Farmers practicing soybean monoculture had significantly lower perception scores on ecosystem services (−5.1 ± 3.8) than to the other four evaluated groups. Overall, the study highlights the critical role of incorporating local knowledge and perceptions for the design of effective management strategies to increase ecosystem services provision and biodiversity conservation in areas adjacent to protected areas.

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1. Introduction

Protected areas are vital for the conservation of biodiversity and the provision of ecosystem services globally. However, many protected areas are managed as isolated islands, disconnected from the surrounding landscapes and communities. This disconnection between protected areas and society affects both nature and human well-being (Hoffmann and Sven Schmeller, 2021). Recognizing and incorporating the needs of communities living next to protected areas is essential for enhancing the effectiveness and sustainability of conservation efforts (Fromont et al., 2024). To achieve this goal, collaborative efforts for conservation and restoration of biodiversity and ecosystem services demand an in-depth understanding of how social issues, local ecological knowledge (LEK), perceptions, and community decision-making influence natural resources management (Lima and Bastos, 2020; De Snoo et al., 2013; Lokhorst et al., 2011). Studies on ecosystem services and biodiversity increasingly recognize the importance of diverse knowledge systems and people's perceptions (IPBES, 2019; Noble et al., 2015). Therefore, integrating LEK and community perceptions of nature is crucial for effective management of ecosystem services and biodiversity (MEA- Millennium Ecosystem Assessment et al., 2005; Tagliari et al., 2023; Teixeira et al., 2018; Lescourret et al., 2015). LEK and perception are closely related, complementary concepts, fundamental in biodiversity conservation, management, and use. LEK is the knowledge system acquired through experience and implicit understanding, accumulated over generations, anchored in everyday life (Berkes and Colding, 2000). On the other hand, perception involves interpreting what is observed, and the importance attributed to a particular resource (Tan et al., 2024). The perception shapes behaviours and actions, reflecting how individuals perceive, think, and react to landscapes, thereby constructing meaningful narratives about them (Stephenson, 2008). The established perceptions, and not just objective scientific evidence, are crucial to ensure local communities support, and thus the success of long term conservation (Bennett, 2017).

Connecting ecosystem services management to the needs, the knowledge, and the expectations of local communities increases the likelihood of success in biodiversity conservation and ecosystem services supply. This connection can foster increased motivation and participation of community members (Jellinek et al., 2019), leading to the recognition and prioritization of specific ecosystem services and biodiversity systems to be conserved (Cáceres et al., 2015). Moreover, it validates the reciprocal relationship between humans and ecosystems, with ecosystem services derived from biodiversity and the environment, and promoted by communities (Comberti et al., 2015). Integrating the knowledge and perceptions of farmers living near protected areas about ecosystem services management and biodiversity conservation is challenging due to the dual functionality of these areas. On a hand, there are fully protected areas dedicated to conserving biodiversity and preserving essential ecological processes, where use of biodiversity is either prohibited or limited (Brazil, Law number: 8,629 of February 25, 1993). On the other hand, agrarian settlements have been established near or adjacent to these protected areas. These settlements originated from the agrarian reform (Brazil, Law number: 8,629 of February 25, 1993). They are rural spaces comprising independent agricultural units engaged in farming and/or livestock activities, relying mostly on family labour (Incra, n.d.). In this context, shared management is crucial to create landscapes that work for both nature and people (Kremen and Merenlender, 2018). This approach effectively creates human issues concerns while enhancing connectivity between conservation units, potentially impacting more than the new protected areas (Brennan et al., 2022). Including LEK into management not only underscores the role of local actors as knowledge providers but also increases the likelihood of these actors utilizing research findings to enhance ecosystem services (ES) provision and landscape modelling (Messina et al., 2023).

LEK has been widely used in research on ecology, biodiversity conservation, and ecosystem services, ranging from guidance on ecological restoration of sensitive degradation-prone areas (Long et al., 2003) to resource management in protected areas (Ban et al., 2009), monitoring of species abundance and richness (Afriyie and Asare, 2020), biodiversity protection, and provision of ecosystem services (Cebrián-Piqueras et al., 2020). Similarly, local perception has significantly contributed, especially in studies on landscape dynamics (Davidson-Hunt and Berkes, 2003), perceptions of biodiversity elements, and analysis of ecosystem services maintenance (Cáceres et al., 2015). The approach involving LEK and perceptions has been valuable in complementing conventional ecological research, speeding up processes that are often costly and time-consuming (Moller et al., 2004), by incorporating insights from individuals with extensive experience and daily familiarity with the areas, benefiting researchers, managers, and policymakers (Halme and Bodmer, 2007). The extensive literature focuses on determining how LEK and perceptions shape communities, revealing insights about natural resources and conflicts (Teixeira et al., 2019), preferences (Lima and Bastos, 2020), and management descriptions (Tomasini and Theilade, 2019; Mashamaite et al., 2023). Understanding how local ecological knowledge (LEK) and perceptions of local populations can contribute to conservation goals represents a significant gap in current scientific understanding (Afriyie and Asare, 2020; Cebrián-Piqueras et al., 2020). 2022). Such research efforts can provide a comprehensive perspective for formulating proposals, enhancing management models, and effectively addressing socio-environmental conflicts (Coelho-Junior et al., 2021).

We know that many factors influence the local community in defining and perceiving their environment (Loring et al., 2014). Variations in LEK and perceptions are complex and diverse due to socio-ecological differences (Verweij et al., 2010). For example, LEK and perception vary among people of different ages, genders, lengths of residence, and forms of contact with natural areas (Hitomi and Loring, 2018). Optimizing the application of LEK and perception is necessary, considering the complex factors that influence their variations (Quintas-Soriano et al., 2016). In this context, machine learning can significantly contribute by analyzing complex data with multiple variables, reducing multicollinearity issues, and identifying patterns and non-linear relationships (Speiser et al., 2019; Rios et al., 2022).

The objective of this study is to determine how various socio-ecological variables, including the use and conservation of biodiversity and the ecosystem, and the farm's production system influence the development and maintenance of local values through machine learning test, in addition to elucidating characteristics of farming families, to explore links between LEK, perceptions and the management of ecosystem services. To this end, we structured this research to answer the following question: What socio-ecological variables influence LEK on biodiversity and farmers' perception of ecosystem services? And complementarily, how do these socio-ecological variables vary with LEK and the perception of ecosystem services?

We conducted this research using interviews and participatory methodologies to assess socioecological variables, farmers' perceptions, and local ecological knowledge. We employed artificial intelligence machine learning techniques to identify the key socioecological variables influencing LEK and the perception of ecosystem services. Subsequently, we estimated the variability of the most important variables employing descriptive statistical, inferential tests, and data flow analyses. Finally, we explored the factors influencing local knowledge, perception and proposed elements to enhance the management of ecosystem services.

2. Materials and methods

2.1. Study areas

We conducted this study in the Cerrado biome, in the central region of Brazil, where there are a diversity of landscapes of savannas, grasslands, and forests (Ribeiro and Walter, 2008). The Cerrado is the most biodiverse savanna on the planet, harboring one-third of Brazil's biodiversity and featuring a high level of endemism (Klink and Machado, 2005). Despite its biodiversity, only 3% of the biome is strictly protected (Françoso et al., 2015), making it one of the critical areas for biodiversity conservation and maintenance of ecosystem services on the planet (Silveira et al., 2016). We selected four agrarian reform settlement in the buffer zone of strictly protected areas, three of thme bordering the protected areas and one not. We considered a 10 km buffer zone, a distance commonly used around protected areas in Brazil. Of these, two are in the Federal District, Pre-settlement Chapadinha, adjacent to the Brasília National Park (42,355 ha), and Settlement Pequeno Willian, adjacent to the Brasília Agricultural College District Park (527 ha), and two in the State of Goiás, Pre-settlement Esusa, adjacent to the Catarata Rio dos Couros State Park (5000 ha), and Silvio Rodrigues Settlement, in the buffer zone of the Chapada dos Veadeiros National Park (24,611 ha) (Costa et al., 2022) (Fig. 1). From now on, we will refer to these settlements as Chapadinha, Pequeno Willian, Esusa, and Silvio Rodrigues. These areas are important for family farmers who have received official documents as owners, reducing real estate speculation and potentially contributing to producing essential food for the population. There are 45, 50, 22 and 119 family farms in Chapadinha, Esusa, Pequeno Willian, and Silvio Rodrigues, respectively (Incra, n.d.).

2.2. Selection of farmers

We randomly selected 142 farmers from the four agrarian settlements and then, either by phone or in-person, invited them to participate. To select the farmers, we used the criteria: living on the farm for more than 5 years, age >18 years old, and having a productive agricultural system on the farm for self-consumption, commercialization or to provide other ecosystem services. Based on the criteria above, 80 farmers participated, representing 35% of the occupied farms in each settlement.

2.3. Socioecological data

Conservation, which depends on understanding human interactions with nature, emphasizes the crucial role of in-person interviews with local stakeholders (Aglissi et al., 2024). Local ecological knowledge and perception should then be obtained through interviews aided by questionnaires (Jew and Bonnington, 2011; Luiselli, 2024).

To collect the socio-ecological variables, we conducted 80 interviews, following prior consent from each participant. The interviews and 54-questions questionnaire were approved by the Ethics Committee of the University of Brasília (CAAE: 30,574,620,000,005,540) and applied to the primary family member.

We selected 13 socio-ecological variables, which have already had their importance tested for LEK and perception (Vuillot et al., 2016; Hitomi and Loring, 2018; Teixeira et al., 2018; Cebrián-Piqueras et al., 2020; Lima and Bastos, 2020): income, age, gender, education, farm size, time living in the farm, biome of origin, contact with conservation and restoration initiatives, way of learning about biodiversity, interactions with Conservation Units (UCs) and Legal Reserve (RL) (determined as protected areas for conserving biodiversity), type of agroecosystem on the farm, and use of natural cerrado areas within the farm.

2.4. Local ecological knowledge (LEK)

The interaction with the 80 participants was dialogic and immersive, incorporating images to illustrate species, landscapes, and descriptions of concepts. To assess the level of LEK about biodiversity, we used predefined knowledge categories with scales (Cebrián-Piqueras et al., 2020). We categorized four distinct types of LEK: 1 – ecosystems

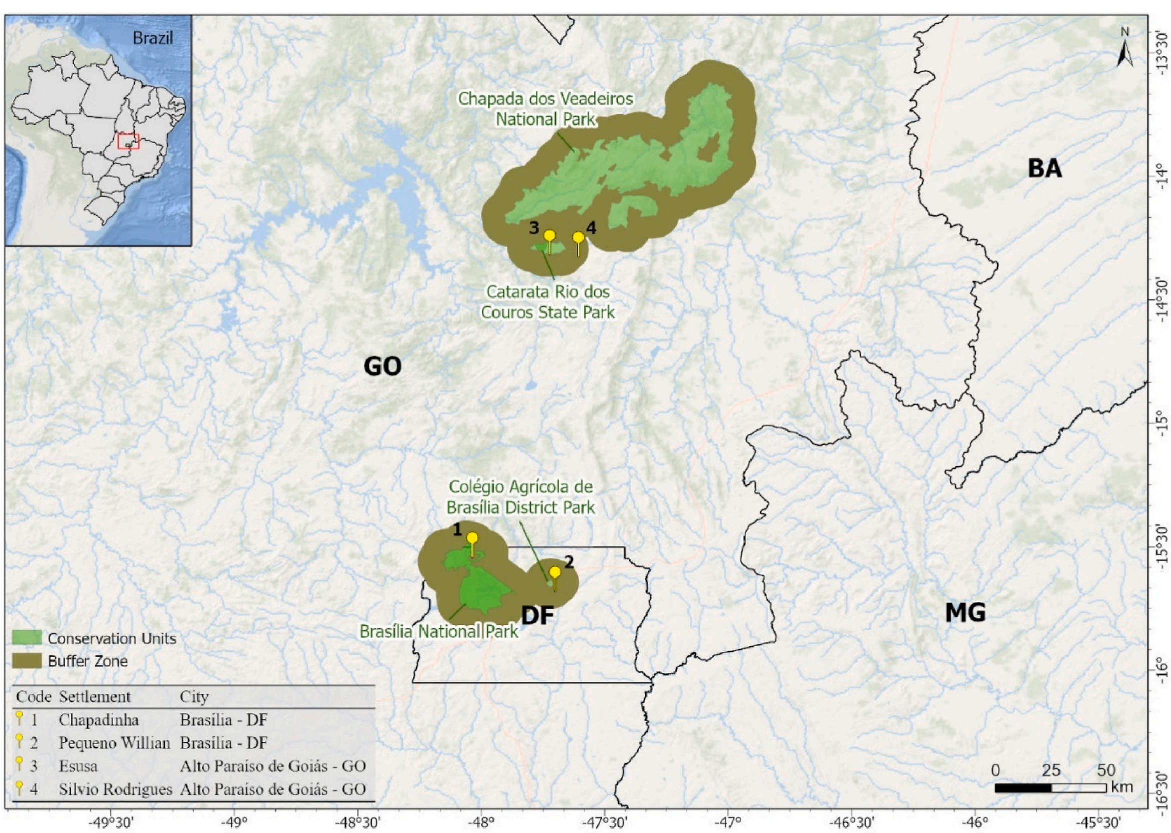

Fig. 1. Map with the location of agrarian settlements adjacent to or close to the Conservation Units. Conservation units are marked in green and buffer zone in brown. The settlements are represented with the yellow pin: 1-Chapadinha; 2-Pequeno Willian; 3-Esusa; 4-Silvio Rodrigues.

(Cerrado plant physiognomies, conservation, and degradation); 2 - species (native, exotic, endemic, invasive and threatened); 3 - use of native plant resources; and 4 – practices (management) for conservation and restoration of ES. We asked interviewees for their knowledge of "Ecosystems" to address distinct characteristics of environments and plant physiognomies of the Cerrado biome. For the variable "species", we requested concepts and meanings attributed to native, exotic, endemic, invasive, and threatened species. To evaluate the use of plant resources, we asked about native plants of the Cerrado, the number of species used daily, the identification of these species and their use by the farmer. Regarding the conservation and restoration practices variable, we recorded which practices were implemented in the farms.

Participants who had not provided information related to the LEK categories received zero points. Farmers who presented detailed information about species, ecosystems and natural landscapes, used native plant resources and implemented conservation and restoration actions for ecosystem services were assigned maximum score. Scores were assigned in units, for instance, one unit for recognition and description of the functions of a plant physiognomy, two units for recognition and description of the functions of two plant physiognomy and so on. The total score (0–60) indicated the participants' final LEK score. This final LEK score was composed of the sum of the four LEK category scores, each ranging from 0 to 15. Other authors (Cebrián-Piqueras et al., 2020) chose to use a weighted scale. The linear scale allowed us to make direct comparisons without assigning different weights to each category based on their importance. Participants demonstrating exceptional details and providing a variety of examples could earn two additional points, potentially scoring 62 points.

2.5. Perceptions of ecosystem services

We examined the perceptions of 80 farmers regarding ecosystem services operating on their farms. We determined which ecosystem classes and services would be evaluated based on the international CICES 5.2 classification (Haines-Young and Potschin, 2018). We selected and named 13 ecosystem services from the regulation, provision, and cultural classes (IPBES, 2019). We evaluated six regulation ES (quality of groundwater freshwater; moderation and fire control; temperature and humidity regulation; soil formation and protection; pollination and dispersal potential; and biological control), four provision (native plants; animal husbandry; food production; and water supply), and three cultural services (capacity of natural areas within the farm to offer recreation and leisure and de-stress environments; aesthetic appeal with relevant scenic beauty of the farm; and relationship of belonging and identity of the interviewee with the natural areas of your farm).

We used the interview method to collect data inspired by the Q methodology, which converts subjective perceptions into quantitative data (Ha, 2014). We conducted a classification process with a bipolar Q-sort table (projected on the data collection form) ranging from −5 for events of extremely negative importance to 5 for events of extremely positive importance. The scores were assigned as 0 (ES not noticed by my family); 5 (farmer recognizes the presence and efficiency of this ES operating on his farm with extreme importance); −5 (farmer recognizes the deficiency of this ES in his farm and therefore does not benefit from it). In instances where a farmer was unsure about the score or even had doubts about the numerical value to assign to his/her observation, we provided an interpretation script with scores assigned from 1 to 5 points.

To understand farmers' perceptions of ecosystem services and visualize the intensity, direction and group of origin of these perceptions, we included open-ended questions in the interview (Cebrián-Piqueras et al., 2017; Texeira et al., 2018): (1) Do farmers perceive changes for the better, worse or no change over the years and specifically this year in the landscape? (2) What is the perceived change? And (3) Are there factors that could change the provision of ecosystem services in the landscape in the future?

2.6. Types of farms

To classify the farms according to the predominant land use, we asked the following questions to farmers: (1) Is there food production on your farm? (2) Do you sell products or provide services on your farm? (3) Is the production in your farm on an organic base, agroecological or conventional? (4) Does the main income from the property come from products of plant or animal origin, both, or from services on-site or off-site? Additionally, we conducted technical expeditions on the ground to observe various elements such as the presence of machinery, types of agricultural inputs used, production area, and area of services used. These observations helped us to define the predominant land use and primary purpose of every farm, and then to define the types of farms. Following the questionnaire and our on-site visits to the properties, we classified farms using a dichotomous key (supplementary material) into: (1) self-consumption; 2) soybean monoculture; (3) ecotourism; (4) animal production in silvopastoral system, focused on animal products commercialization; and (5) agroecological, who produce plant products for commercialization such as seeds, fruits, and vegetables.

2.7. Data analysis

To address the question, "What socio-ecological variables influence LEK and farmers' perception of ecosystem services in settlements near to conservation units?", we employed artificial intelligence machine learning techniques, specifically the Random Forest modelling. We chose Random Forest due to its high classification accuracy, robustness against noise and outliers, as well as its ability to handle large amounts of data simultaneously without overfitting (Zhao et al., 2022). We analyzed the influence of 13 socio-ecological explanatory variables on LEK and perception (response variables). With the "Feature Importance" process, we evaluated the contribution of each variable in reducing impurity within individual decision trees. The more a variable is used to make divisions in the trees that improve purity, the more important the variable. The relative importance of each variable to the model is indicated by "%IncMSE", with values exceeding 30 indicating high influence (Genuer et al., 2010). Then, we assessed the variability of the most important socio-ecological variables associated to LEK and perception. For this, we performed ANOVA (Analysis of Variance) to capture significant variations of the explanatory variable concerning the response variable. Tukey's post-hoc test was used to analyze significant differences between the subgroups of the variables. For non-parametric data, we used the Kruskal-Wallis test, followed by Dunn's test to indicate which pairs of groups differ significantly.

3. Results

3.1. Socioecological aspects

We interviewed 44 men (55%) and 36 women (45%). Farmers from the four agrarian settlements ranged in age from 18 to 79 years old, with the majority (73.7%) under 60 years old. The majority (77.7%) have a monthly income of less than $545 Although 81.2% of respondents attended school, only 15% completed higher education. More than half (55%) of farmers were born in the Cerrado biome, and the vast majority (84%) have lived on their farms for between 5 and 20 years. Most of the farms (91.2%) exceed 6 ha in size, with 31.5% smaller than 10 ha.

Among the respondents, 60% had visited the conservation units near their settlements, and 73.7% explored the Legal Reserve areas at least once (Supplementary Material). Over half of the farmers (53.7%) reported contact with nature conservation and restoration initiatives. Most farmers (75%) use natural areas of typical cerrado, either for non-wood products (72.5%) or wood resources (2.5%). Among the farmers using non-wood products, 33.7% solely collect fruits, while15% collect a variety of items, including fruit, bark, resins, straw, fibers, roots, medicinal plants, seeds, and leaves. Furthermore, 17.5% of farmers use typical cerrado vegetation areas for livestock, and only 6.25% primarily use these areas for leisure, recreation, educational activities, and stress relief. (Supplementary Material)

Most of the farms (72.5%) focus on the production of products and services for commercialization. Among those almost half (33.7%) are based on agroecological vegetable production for commercialization (15% have organic certification); animal production (12.5%), soybean monoculture (18.7%), and ecotourism (7.5%). The remaining farms (27.5%) focus on the production aimed at farmers' family self-consumption.

3.2. LEK

We asked the farmers what their primary source of acquiring Local Ecological Knowledge (LEK) was. The majority of farmers (70%) reported gaining knowledge through the use of natural cerrado environments. Only a small percentage (13.7%) mentioned generational transmission as a source of knowledge, while an even smaller number (7.5%) cited contact with conservation and restoration initiatives. Notably, a very small proportion of farmers attributed importance to websites, television, videos (3.75%), contact with neighbors and friends (3.75%), and formal education (1.25%) as their main learning methods.

LEK levels varied considerably among farmers. Most farmers (81.2%) recognized at least one plant physiognomy of the Cerrado biome, the typical cerrado being the vegetation most known (61.2%). Only 12.5% of the farmers recognized and differentiated all five plant physiognomies presented in photos (typical cerrado, rocky cerrado, open cerrado, paths, and forests). Likewise, only 12.5% of farmers were familiar with all five types of species: native, threatened, exotic, invasive, and endemic. Approximately two-thirds (66.2%) correctly described native species with their concepts and meanings. The majority (73.7%) presented knowledge of native plants and confirmed frequent use, primarily for food and medicinal purposes. However, conversely, a sizable portion (62.5%) of farmers reported they had not engaged in practices for conserving natural areas and restoring ecosystem services on their farms. (Supplementary material)

3.3. Perception about ecosystem services

Negative changes impacting the provision of ecosystem services over the past five years in the settlement were mentioned by more than half (52.5%) of the farmers, who highlighted changes in the landscape that affected their farms. The majority (42.5%) attributed these negative variations to soybean monocultures in the settlement. The remaining farmers reported a decrease in the productivity of native fruit trees (3.75%), decreased quality and quantity of water (2.5%), livestock reduction due to attacks by wildlife (2.5%), and deforestation within farms due to changes of owners (1.25%).

Of those who have positive perceptions (41.2%) that there are improvements, the majority (21.2%) attributed the improvement to the denser cerrado, which has more trees, which improved climate, water quantity and other services. Additionally, 13.75% of the farmers attributed the improvement in the natural landscape to the agroecological food production for commercialization and that also ensured food security for farmers' families. The acquisition of suitable housing and infrastructure (opening dirt roads and access to electricity) was mentioned by 3.7%, and the designation of independent spaces for production and conservation by 2.5%. Only 6.2% cited the absence of any type of change in the landscape over the years.

Most farmers (92.5%) believe that the provision of ecosystem services in the landscape will change. Of these, 38.7% believe that the change will be due to the presence of soybean monocultures, deforestation for soybean planting, frequent use of pesticides and the presence of soybean pests in vegetables and native trees. The remaining 22.5% say that land insecurity or the lack of regularization of agrarian reform settlements will compromise the provision of ecosystem services in the landscape, due to speculation in rural and natural areas that will change to areas with urban characteristics and for grain production. There is a group (10%) that believes that the main threat is the financial insecurity of families, which can cause them to migrate to a predatory system that affects regulatory ecosystem services, such as the removal of wood or monoculture soybean cultivation. Only 8.7% attributed changes in the provision of ecosystem services to climate unpredictability, such as changes in rainfall patterns, extreme torrential events or extreme droughts, and a decrease in the flow of water available for family use.

For 6.2% of farmers, the future concern is fires that could result in loss of ecosystem services and 5% believe that the main threat is invasive exotic species, in which case two species are mentioned (*Urocloa decumbens*, the signal grass, and *Tithonia diversifolia,* the Mexican sunflower). With the opposite perception, 7.5% indicated that ecosystem services will not be affected in the landscape. These describe that the environment has sufficient attributes for the maintenance and resilience of ecosystems. Farmers from all farm types, including soy-bean farmers, reported that soy monocultures are expected to have a negative effect on the landscapes (Fig. 2).

3.4. Predictive model

The results of the Random Forest modeling reveal that the LEK of families in rural settlements is highly influenced by two variables: the level of contact with conservation and restoration initiatives, and the direct contact and use of natural areas of typical cerrado, both above 30% IncMSE. Formal education and the link between farmers and the environmental protection area neighboring the settlement are variables of medium importance. The remaining variables contribute less significantly (Fig. 3a). The perception of ecosystem services by farmers is mainly determined by the type of agricultural activity carried out on the farm. Farmers' age, length of residence in the settlement, farm size, and use of natural cerrado areas on the farm have a limited effect on farmers' perceptions of ES (Fig. 3b). The model demonstrates its best robustness at a low value of the cross-validation mean squared error (CVMS)E) (Varmuza and Filzmoser, 2009). Therefore, the influence of all variables is not invalidated, considering that the two models, also using the 13 predictors, are cross validated with CVMSE with good robustness (supplementary material, appendix E). According to cross-validation, for LEK, four variables are sufficient for a good model. For perception, based on the minimum CVMSE value, one variable guarantees good accuracy for the model (supplementary material, appendix E). The learning machine demonstrated robustness in evaluating factors that affect LEK and perception. This can improve ecological research by filling gaps, especially in quantitative approaches related to local knowledge (Steele and Shackleton, 2010).

3.5. Structural assessment

We tested for differences in LEK and perception considering: the most important variables identified in the Random Forest model and, the number of predictors selected by cross-validation.

The Random Forest model shows that the variable most strongly affecting LEK is the participation of farmers in conservation or restoration initiatives. The level of LEK of farmers differed based on their form of participation in conservation or restoration initiatives ($F = 10,715$; p-value <0.001; ANOVA). Farmers with no participation had a significantly lower level of LEK ($11,4 \pm 5,9$) than farmers with full participation ($28,5 \pm 13,0$; valor $p = 0.012$) and farmers with a contract ($26,2 \pm 14,5$; valor $p < 0,001$). There were no significant differences in LEK between farmers who observed initiatives ($18.5 \pm 6,4$) or developed initiatives on their own ($20.7 \pm 15,8$) and the other categories (Fig. 4a). The way the cerrado is utilized significantly explained the variation in farmers' LEK ($F = 4095$; p-value $= 0.00271$; ANOVA). Farmers who used cerrado for cattle farming ($12,8 \pm 6,8$; valor $p = 0.039$) and those who did not use the cerrado ($13,5 \pm 8,9$; valor $p = 0.019$) had a significantly

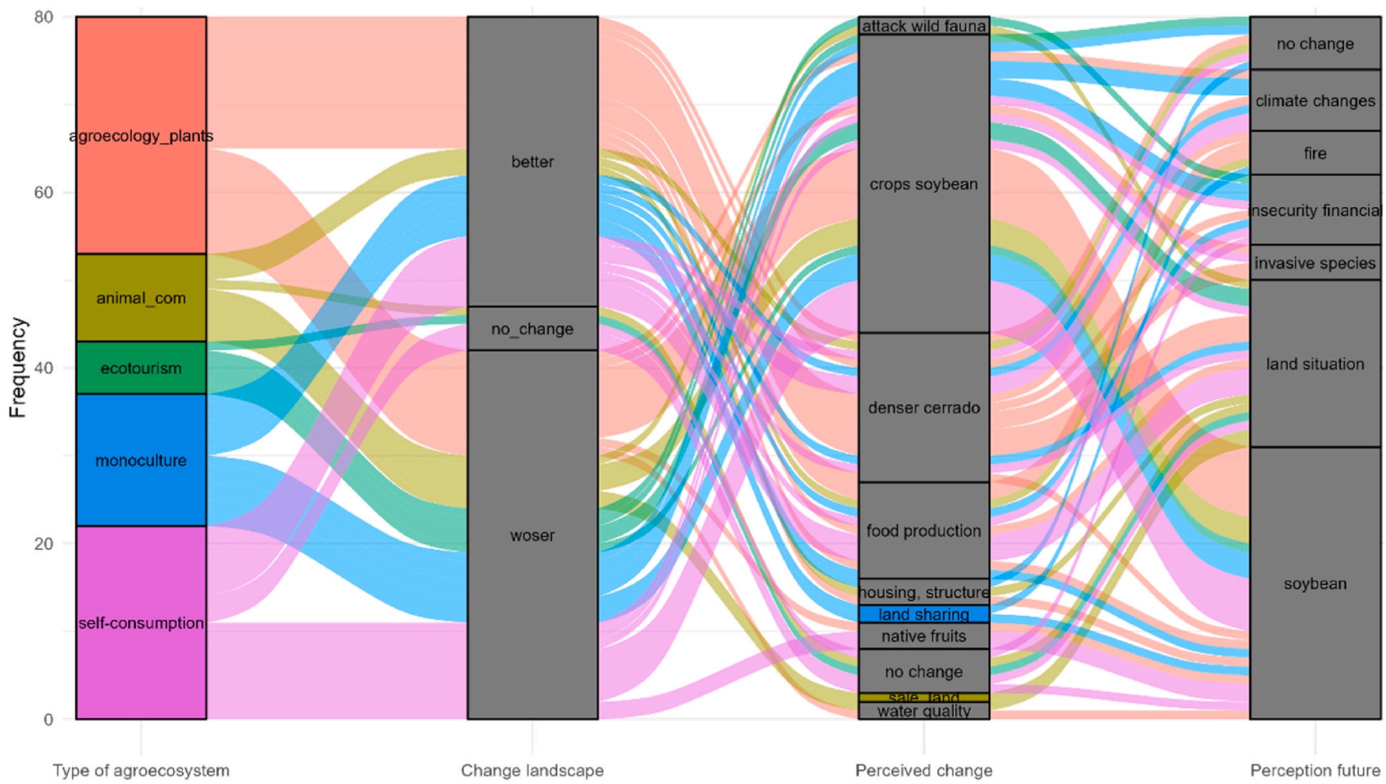

Fig. 2. Perception of different types of farmers regarding landscape changes and future threats. The figure presents the relationship between types of agroecosystems (first column), positive, neutral, or negative changes in the farm's landscape (second column), types of perceived changes (third column), and main future threats to the farm (last column). The agroecosystem categories include plant agroecology, animal farming, ecotourism, monoculture, and self-sufficiency. The perceived changes in the landscape range from better, no change, to worse. Future threats include climate change, fires, financial security, invasive species, land situation, and soybean cultivation.

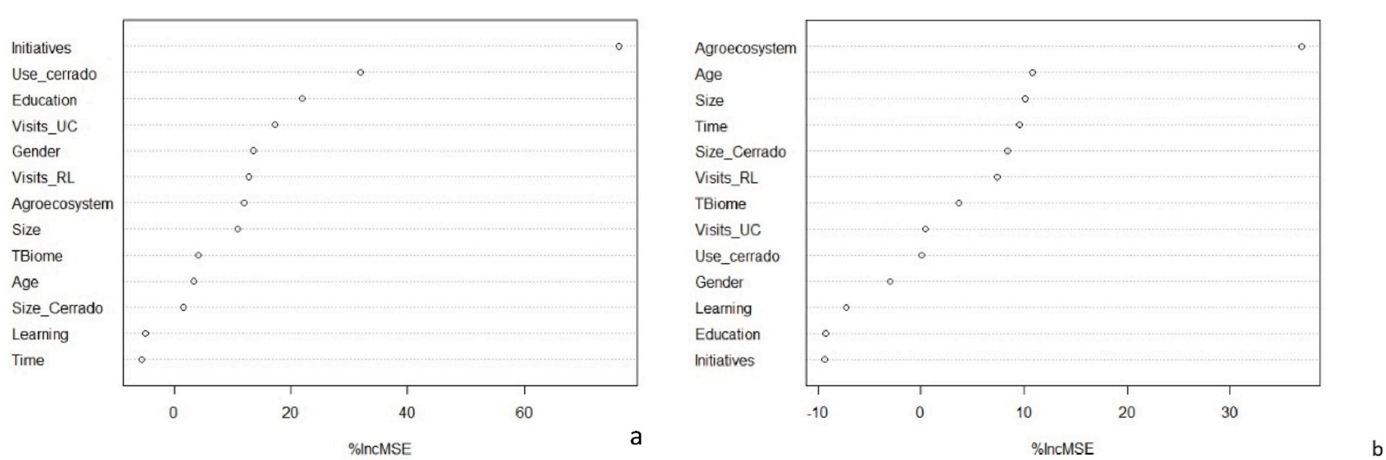

Fig. 3. Random Forest model with influence variables on the target variable (a) LEK and on the target variable (b) perception. "%IncMSE" is the percentage of the mean squared error, which determines the importance of the individual variable for the model.

lower level of LEK than farmers who used the cerrado for leisure and education (28,2 ± 21,2), p-value = 0.001). There were no significant differences in LEK between farmers using cerrado for agroextractivism (21,0 ± 13,9), intense extractivism (26,5 ± 13,2), and timber extraction (15,0 ± 15,6) and the other categories (Fig. 4b). The level of education did not significantly explain the variation in LEK (F = 2498; p-value = 0.067; ANOVA), and the post hoc test also showed no significant differences between the different levels (Fig. 4c). The subgroups evaluated for the category of links with UCs (F = 2528; p-value = 0.087; ANOVA), based on the number of visits to these areas, do not differ in terms of importance in the LEK, and the post hoc test also showed no significant differences between the different levels (Fig. 4d).

The type of activities carried out on the farm (agroecosystem) significantly explained variation in farmers′ perceptions on ecosystem services ($X^2 = 29.96$; $p < 0.001$; Kruskal-Wallis). Farmers who practice soybean monoculture scored significantly lower (−5,1 ± 3,8; valor p < 0,001) in comparison to the other four groups, in Dunns' test (Fig. 4e).

The results indicate that conservation and restoration initiatives integrated with stakeholders, as well as the use of native cerrado areas, particularly for recreational activities and educational trails, should

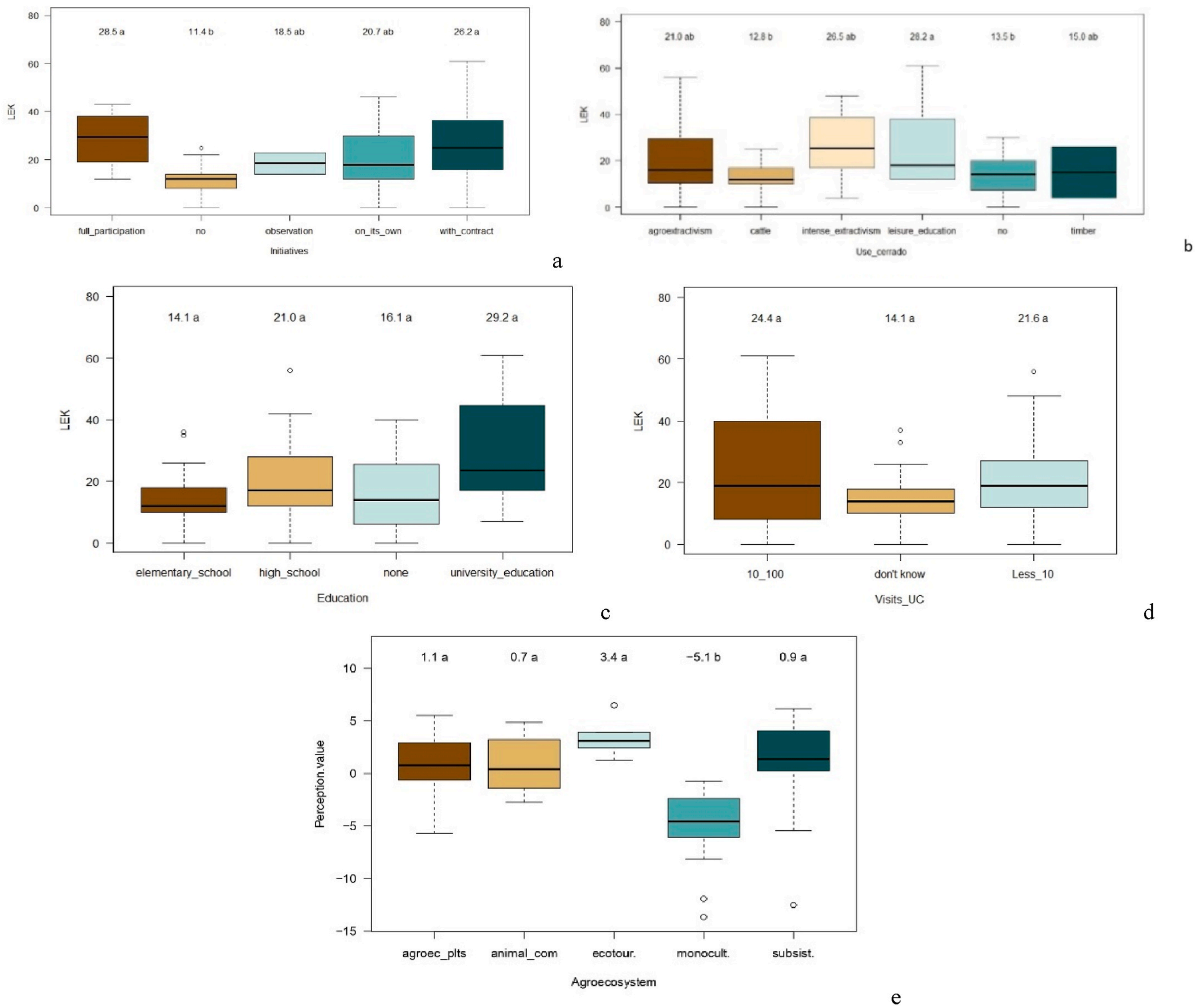

Fig. 4. Importance of variables in LEK **(a–d)** and perception **(e)**. **(a)** Contact with nature conservation and restoration initiatives concerning LEK; **(b)** Use of the cerrado in relation to LEK; **(c)** - Education in relation to LEK; **(d)** Link with the conservation unit neighboring the settlement in relation to the LEK; **(e)**Variation in internal structure based on type of agroecosystem in relation to perception. Box indicates the interval between quartiles 1 and 3, horizontal line indicates the median, whiskers indicate the extent of the data and individual points the outliers. Different letters indicate significant differences $p \leq 0.05$; Tukey test).

improve or maintain levels of local knowledge. For perception, the best results will occur when approaches for improving ecosystem services management are specifically planned and implemented for each type of farmer. These actions are capable of guiding decisions for management and planning, which would certainly increase the likelihood of maintaining biodiversity and enhancing the provision of ecosystem services in a sustainable manner (Fig. 5).

4. Discussion

4.1. The participation of farmers in initiatives and the use of natural areas are crucial for LEK

Previous studies have established that communities with robust governance systems, effective external alliances, and sustainable practices in natural areas demonstrate high levels of LEK (Mutenje et al., 2011; Soriano et al., 2017). This was somewhat replicated in our study. The results align with this understanding by suggesting that higher levels of LEK are achieved by farmers engaged in local actions.

Involvement in “nature conservation and restoration initiatives”, particularly those conducted by and within communities, emerges as the most important factor contributing to Local Ecological Knowledge (LEK), especially when farmers actively participate in all phases of the project. Developing local planning processes with active community participation, rather than relying solely on external interventions can foster more equitable results for ecosystem services management (Dorresteijn et al., 2017). Moreover, valuing LEK in decision-making processes and maintaining open channels to diverse knowledge systems proved to be effective strategies for the maintenance, conservation, and management of ecosystem services (Díaz et al., 2015). Dialogic and participatory events can deepen understanding of ecosystem services and the interconnections between biodiversity and ecological processes. This can enhance farmers’ voluntary engagement in conservation efforts (Bennett, 2017), and also facilitate the co-creation of local solutions for ecosystem management (Tengo et al., 2017; Teixeira et al., 2018).

When setting goals for the conservation and restoration of ecosystem

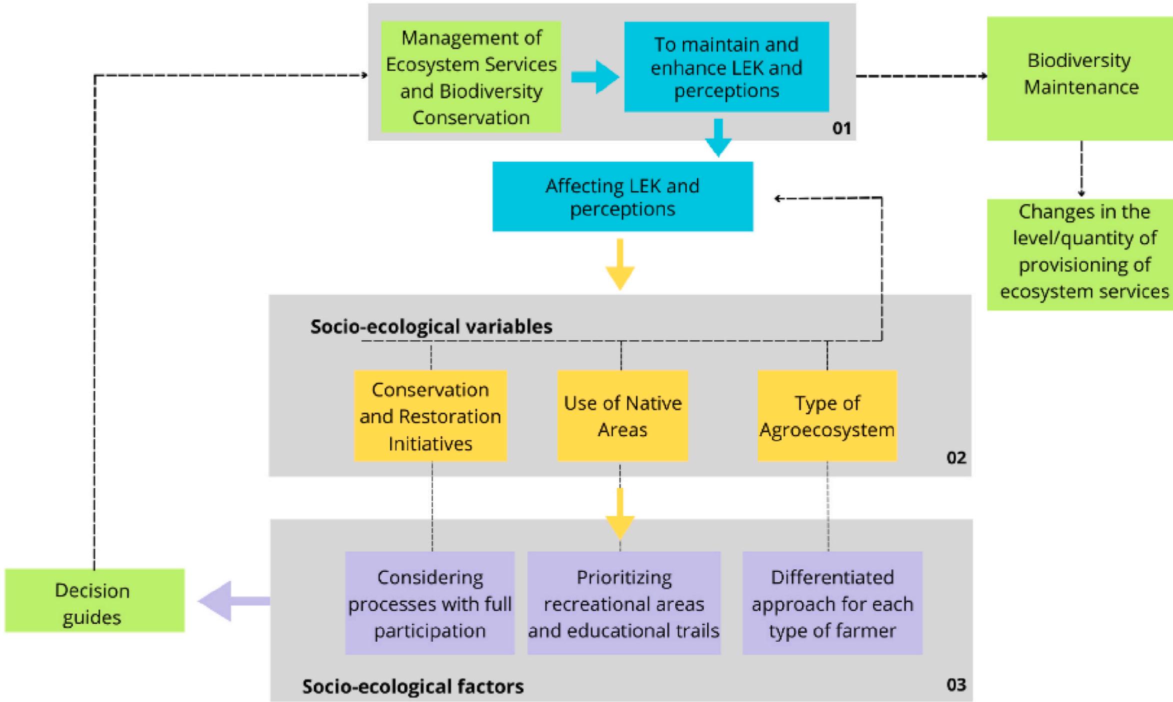

Fig. 5. It shows a strategy to improve the management of ecosystem services: (1) understanding that socioecological systems depend on local ecological knowledge (LEK) and perceptions, (2) understanding which socioecological variables influence LEK and perceptions, and (3) deriving the analysis of variables into factors that, in turn, can improve management strategies.

services, it is crucial to acknowledge the diverse motivations of the involved communities and evaluate potential ecological and social benefits (Jellinek et al., 2019). In communities near protected areas, local participation in conservation goals is essential. This involves promoting collaboration in resource conservation, facilitating the sharing of decisions and priorities, and identifying needs with all stakeholders.

Our findings further indicate that the use of natural cerrado areas is also highly relevant to Local Ecological Knowledge (LEK). First, when directly asking farmers, the primary way of acquiring LEK was determined to be contact with natural areas. Complementarily, machine learning also highlighted this high influence. Finally, the internal structural analysis pointed out that educational and recreational activities, i.e., activities promoting cultural ecosystem services, result in high levels of LEK, significantly differing from other uses of the cerrado. This suggests that local populations are highly engaged with the surrounding ecosystems and that their ability to provide cultural ecosystem services, such as recreation, environmental interpretation trails, or hiking, are influential actions in cultural identity (Soriano et al., 2017).

By fostering approaches that strengthen cultural identity, are inclusive and participatory, we can enhance the effectiveness and sustainability of ecosystem service management, while also addressing the diverse needs and aspirations of local communities.

In a general analysis, education showed medium relevance but was not significant for local ecological knowledge (LEK), similar to the relationship with legal reserve area and gender. Other studies have reported inconsistent associations between education levels and the constitution of LEK (Berkes and Colding, 2000). However, they confirm that gender can be highly significant for LEK (Souto and Ticktin, 2012). Age did not show to be relevant to LEK. Studies warn that in many cases, older individuals were chosen to report on LEK, causing a bias in understanding that age influences high levels of LEK (Steele and Shackleton, 2010). However, in comparative studies between ages and LEK, it was demonstrated that age differences do not significantly affect LEK (Steele and Shackleton, 2010; Dovie et al., 2008). The length of time a farmer has lived on the farm was not relevant to LEK in our study, similar to findings in another research (Cebrián-Piqueras et al., 2020). However, we found incentives to investigate the variable time differently fri Iniesta-Arandia et al. (2014) found that the time spent by the farmer in the area proved to be highly relevant to LE.

4.2. *Farmers perception of ecosystem services is primarily associated with the agroecosystem cultivated within the farm*

The predominant land use and primary purpose of every farm, which defines the agroecosystem type, significantly influences farmers' perceptions of ecosystem services, similar to findings of other studies (Teixeira et al., 2018; Aguado et al., 2018; Adeyemi et al., 2022). Community members involved in occupations and lifestyles closely tied to the preserved environment or near the original landscape have a greater awareness and understanding of ecosystem services (Ke et al., 2024; Dehghani Pour et al., 2023). On the other side, we found that family farmers who adopted soybean monoculture systems on their properties have a negative perception of ecosystem services. Therefore, it is crucial to consider how different types of farmers perceive ecosystem services when managing areas. The choice of production model by farmers continues to shape their perception over time, as they increase their understanding of their production systems, leading to a stronger appreciation of biodiversity, conservation and the potential for ecosystem services provision (Teixeira et al., 2018). Ecosystem service management programs must therefore acknowledge the diverse types of family farmers. Diverse types of farmers and their abilities to provide various ecosystem services can play a key role in promoting biodiversity conservation and ecological functioning at a landscape scale (Kremen and Merenlender, 2018). By recognizing and adapting to the evolving perceptions and needs of farmers, managers and policy makers can enhance the effectiveness and sustainability of ecosystem service management initiatives.

It is still valid to categorize the points of convergence and divergence in the perceptions of different groups (Teixeira et al., 2019). When discussing future perspectives on the maintenance of ecosystem services in this research, all types of farmers agreed that soybean monocultures at some point will have a negative effect on landscapes altering the provision of ecosystem services. Although a group adopts a specific technique which negatively impacts the ecosystem services, biodiversity and the environment, its critical capacity to recognize harmful effects on the environment is not invalidated. The disconnect between perception and the execution of activities raises the question of the role of social differences or barriers in social/political networks in driving actions disconnected from perceptions (Mclean et al., 2022). Initiatives that highlight contradictions between farmers' actions and perceptions can drive changes, useful in conservation transitions planned with the community.

Age had only secondary relevance in perceptions of ecosystem services (ESs). Previous studies have also reported age as having lower relevance (Ke et al., 2024; Koju et al., 2023). Education was found to be irrelevant to perception in this study, contrary to another study (Dehghani Pour et al., 2023), where the respondent's education influenced the perception of certain ecosystem services.

Conservation and restoration initiatives within communities did not influence farmers' perceptions of ecosystem services, suggesting that perception formation in these communities may be more closely tied to deep everyday experiences rather than specifically associated with actions, projects, and workshops in the area, or contact with external individuals.

4.3. Strategies for Ecosystem services management and biodiversity conservation

Our study highlighted critical socioecological components, emphasizing essential actions for the preservation and valorization of local ecological knowledge and the enhancement of perceptions regarding ecosystem services. Based on these findings, we ask: what strategy can be utilized to improve the management of ecosystem services and biodiversity conservation? We propose that actions promoting the increase of local ecological knowledge and perceptions can permanently connect people to resource management, done in an integrative and adaptive manner to maintain ecosystem services and conserve biodiversity.

The mediation between socioecological variables and local knowledge can induce changes in the quality and quantity of these services, jointly supporting biodiversity and human well-being (Gu and Subramanian, 2014). Therefore, it is necessary to identify the drivers of change, namely the socioecological factors that influence the increase in local knowledge and percepetion. Understanding the socioecological factors of the community surrounding protected areas provide insights into the prevailing dynamics and adjustments needed for integrated management (Kremen and Merenlender, 2018).

Participation levels in conservation, management, and restoration initiatives, as well as the utilization of native cerrado areas within farms are key factors positively correlated with LEK concerning ecosystem services and conservation. Furthermore, the type and purpose of the primary activities conducted within farms strongly shape farmers' perceptions of ecosystem services. Therefore, to enhance the success of initiatives aimed at conserving biodiversity and ensuring ecosystem services in protected areas and their environs, it is fundamental to involve farmer communities in all stages of these initiatives. Moreover, the needs and aspirations of these communities must be integrated into the planning and execution of conservation efforts. Finally, since LEK and perception are dynamic and continually evolving, management strategies must adapt to these changes over time.

4.4. The potential of using machine learning for local value influence analysis

Our findings indicate the importance of using machine learning to identify the most influential socio-ecological variables for both LEK and perception, a task that might have been overlooked using traditional model-building approaches (Rahal et al., 2022). With the Random Forest algorithms, we were able to determine the relative importance of the thirteen socio-ecological variables tested, highlighting the necessity of incorporating such data to assess variation in local values.

The use of machine learning data to inform public policies and intervention opportunities based on predictive modelling (Risi et al., 2019) strategically identifies influential variables shaping local value systems and environmental management. This approach enables decision-makers to allocate resources where they maximize the benefits of ecosystem services. The decision-making process involves highlighting how certain socio-ecological variables impact local values and, consequently, the supply and demand for ecosystem services. Therefore, machine learning tools can not only enhance decision-making processes but also facilitate the creation of actions aligned with local values, thereby promoting effective conservation and management strategies.

4.5. Research limitations

The social desirability bias can influence interviews, as participants may provide answers they perceive as socially acceptable rather than entirely truthful (Luiselli, 2024). This became evident during the pilot phase of the interviews. To mitigate this limitation, we sought to develop actions that would increase the trust of farming families to the point where they felt comfortable being honest, providing answers that reflected reality.

We held discussions with settlement leaders, presenting the research method and questionnaire to align the research objectives with the community's feedback needs. Additionally, we trained four extension workers experienced in agrarian reform settlements to build trust with the farming families, particularly during guided walks within the farms. Only after this stage and at a spontaneous moment, when the families indicated they were ready for the interview, was the interview conducted.

Although the interview was directed at one family member, we invited other members to join, believing this helped validate what was being said. The questionnaire included open-ended questions that contributed to maintaining a spontaneous dialogue, where the interviewer avoided asking questions directly. We concluded that in-person meetings offer high levels of interaction, which is recommended to overcome the challenges of research like this.

5. Conclusions

Our study reveals the critical socio-ecological variables that influence Local Ecological Knowledge (CEL) and perception among farmers living in agrarian settlements adjacent to protected areas in the Cerrado biome, with the purpose of determining which factors should be considered in strategies that can improve the conservation of biodiversity and the provision of ecosystem services.

Summary of Findings and Implications.

1. Identification of Relevant Variables to LEK:
   - Participation in Conservation Initiatives: Active participation in conservation, management, and restoration initiatives is positively correlated with Local Ecological Knowledge (LEK).
   - Use of Native Areas: The use of native Cerrado areas on farms is strongly linked to LEK, highlighting the importance of sustainable rural tourism practices, such as leisure activities and ecological trails.
2. Identification of Relevant Variables to the Perception of Ecosystem Services:
   - Type of Farmer-Agroecosystem: Farmers' perceptions of ecosystem services are significantly influenced by the type and purpose of the main activities carried out on the farms.
3. Implications for the Management of Ecosystem Services and Biodiversity Conservation:

- Promotion of Community Involvement: Involving agricultural communities in all stages of conservation and restoration initiatives (demand assessment, proposal development, planning, execution, and evaluation) is essential for long-term success and achieving changes in the quality and quantity of ecosystem services.
- Integrative Approach: The needs and aspirations of communities must be considered in the planning and execution of conservation actions. Integrating stakeholders and processes within the territory is fundamental to aligning community interests, thereby keeping the community motivated to contribute to conservation goals.

Recognitions: This work is the result of sensitive and dialogical listening to residents of agrarian reform settlements bordering Conservation Units in Central Brazil. We hope that this research can impact groups interested in strengthening socio-ecological systems and that agrarian settlements can be recognized in their ecological importance and social vulnerability, to receive public policies that value them as a possible group to contribute to the maintenance and addition of ecosystem services.

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CRediT authorship contribution statement

Viviane Evangelista: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Aldicir Scariot:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition. **Heitor Mancini Teixeira:** Writing – review & editing, Validation, Supervision. **Ilvan Medeiros Lustosa Júnior:** Writing – review & editing, Resources, Funding acquisition.

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.

Data availability

I recorded it at the end of the manuscript or in the link to the database. The link is this: https://data.mendeley.com/datasets/yrdhjh37ym/1

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Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122095.

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