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Mismatch between investment in management and priorities for biodiversity conservation in Amazon protected areas

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ABSTRACT

The availability of resources and an adequate management structure are critical for effective biodiversity conservation in protected areas. However, there has been a mismatch between establishing protected areas and investing in their management, particularly in the Neotropical region. This study examines the factors influencing management effectiveness in Brazilian Amazon protected areas and proposes a strategy to prioritize investments based on conservation value and anthropogenic pressures. Our findings indicate that areas supported by the Amazon Protected Areas Program (ARPA) and managed by federal agencies generally have higher management effectiveness and more resources than those managed by state agencies or without ARPA support. Deforestation negatively affects management implementation and is mainly driven by surrounding pressure. We also found that higher-priority PAs for biodiversity conservation, considering threatened mammals and birds and sustainable-use species, tend to have lower management levels and fewer resources. These results underscore the importance of directing investments to high-value protected areas to strengthen their capacity to safeguard biodiversity effectively.

1. Introduction

Establishing protected areas (PAs) is the main strategy to address the global crisis of biodiversity loss (Geldmann et al., 2021; Leverington et al., 2010). Nonetheless, biodiversity decline persists, even within PAs (Geldmann et al., 2013). The effectiveness of PAs in safeguarding biodiversity depends on their ability to withstand anthropogenic impacts, such as deforestation, resource availability for management (Geldmann et al., 2018), and territorial pressures like infrastructure projects and agricultural expansion (Shah et al., 2021). The gap in investment for conserving those areas stem from insufficient political prioritization of environmental agenda (Maxwell et al., 2020). Consequently, many PAs face technical and financial constraints, with 47 % of those listed in the global database lacking sufficient resources, a figure that rises to 60 % in the Neotropics (Coad et al., 2019).

Ecological representativeness and management effectiveness are key metrics for monitoring international conservation goals in PAs (Maxwell et al., 2020). Representativeness represents the biological richness, either of species or ecosystems, assuming that it also reflects biodiversity's long-term persistence (Pressey et al., 2015). Management effectiveness assessments measure administrative attributes and their outcomes, often based on the International Union for Conservation of Nature (IUCN) guidelines (Leverington et al., 2010). Those assessments intend to measure diverse outcomes, including the promotion of socio-economic benefits for local communities and protecting cultural values (Naidoo et al., 2019; Oldekop et al., 2016). Thus, they are more complex to interpret compared to representativeness, but provide valuable insights to inform decision-making (Coad et al., 2015).

The relationship between management effectiveness and ecological outcomes is still poorly defined (Coad et al., 2015). While some studies have found a positive association (Powlen et al., 2021), others have found none (Nolte and Agrawal, 2013; Pellin et al., 2022). In the Amazon, Pellin et al. (2022) noted that reduced resistance to deforestation was more influenced by area accessibility, suggesting that external context plays a larger role than management in acting as a barrier to threats. Similar conclusions were drawn regarding fire outbreaks (Nolte and Agrawal, 2013). Conversely, the Amazon Protected Areas Program (ARPA) significantly increased the capacity of supported

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areas to prevent deforestation, underscoring that improved investment on management can enhance long-term effectiveness (Soares-Filho et al., 2023). Additionally, Geldmann et al. (2018) found that resource availability is positively associated with species population trends within PAs. Given these varied and sometimes conflicting findings, the topic would benefit from comprehensive analyses that capture the complexities of these dynamics. To this end, we use structural equation modeling to assess a causal model that explores the interplay between threat context and the characteristics and management quality of PAs in the Brazilian Amazon.

Given the constraints on resources, prioritizing investments to enhance the effectiveness of PAs through cost-effective strategies is essential (Kullberg et al., 2015). The conservation value of an area depends on which conservation targets are assessed (Kullberg et al., 2015). An inclusive target definition process reflects diverse values and integrates local communities' priorities (Di Minin et al., 2017). Pressure drivers indicate threats to conservation, so areas with higher pressure require greater intervention to ensure conservation (Adams et al., 2019; Kullberg et al., 2015). A reactive prioritization targets areas under severe pressure, while a preventive approach focuses on less vulnerable areas to prevent losses (Ribeiro et al., 2018). Political decisions often lead to biased creation of PAs in remote or low-commercial-value regions (Vieira et al., 2019). Moreover, species representation can be five to seven times lower when considering only areas with adequate resources (Coad et al., 2019). Therefore, systematic planning for investment prioritization can enhance the impact of existing PAs by increasing management efficiency (Kullberg et al., 2015).

In face of the new global target of protecting 30 % of the world's territory (CBD, 2022), it is crucial to allocate investments effectively to manage PAs in a way that meets conservation objectives (Adams et al., 2019). In the Amazon, proper resource allocation is essential as these areas are crucial for forest protection, responsible for preventing over 60 % of the predicted deforestation (Alves-Pinto et al., 2022). Despite their importance, all federal Amazon areas lack sufficient resources for effective management, risking biodiversity maintenance (Silva et al., 2021). Beyond analyzing causal relationships, this study identifies priority PAs for biodiversity conservation and investment in management and assesses whether these prioritized areas have adequate levels of management and resources. Our aim is to provide insights for cost-effective strategies to achieve conservation targets under the Kunming-Montreal Global Biodiversity Framework (GBF).

2. Methods

2.1. Study area

We designated PAs as conservation units established through the National System of Conservation Units (SNUC) under Brazilian Federal Law No. 9.985/2000. While indigenous lands and *quilombola* territories are also recognized as PAs in Brazil under the National Strategic Plan for Protected Areas (Decree No. 5.758/2006), conservation units encompass areas most akin to IUCN categories and benefit from management assessment tools aligned with international standards (UNEP-WCMC, 2019).

The Brazilian Amazon has 28.5 % of its area covered by 381 conservation units, making it the Brazilian biome with the highest protection coverage (MMA, 2024). We analyzed 261 areas (Fig. S1, Table S1), with their spatial delineation obtained through the National Registry of Conservation Units (CNUC) (MMA, 2024).

2.2. Management indicators

We analyzed areas with available data on management effectiveness, assessed by the Brazilian Federal Court of Accounts (TCU), and with georeferenced delineation in the CNUC. Out of the 280 Amazon PAs evaluated by the TCU, we excluded 19 due to lacking valid spatial data. TCU developed the Protected Areas Implementation and Management Index (Indimapa) and applied it in coordinated audits in 2014 and 2019 (TCU, 2021). This methodology relies on 13 indicators scored from zero to three based on responses from PAs' managers via an electronic questionnaire (Table S2). Although based on manager's perception, TCU data offers the advantages of being collected by an external body, compared with data from other sources and having been applied in all units of the Amazon biome, overcoming limitations of other assessments (Geldmann et al., 2015; Leverington et al., 2010; Pellin et al., 2022). For instance, the most recent evaluation using the Rapid Assessment and Prioritization of Protected Area Management (RAPPAM) methodology covered 150 protected areas and was conducted in 2015 (WWF-Brasil, 2017), making it both older and less comprehensive than the TCU analysis. Another national tool, the Management Analysis and Monitoring System (SAMGe) (ICMBIO, 2024), is applied annually but does not yet cover all areas. The most recent data available for SAMGe is from 2023 but includes only 130 Amazon protected areas. Therefore, TCU remains the most up-to-date and comprehensive management effectiveness assessment for Amazonian protected areas.

Indimapa is based on global tools to assess management effectiveness (UNEP-WCMC, 2022), such as the Management Effectiveness Tracking Tool (Stolton et al., 2021). TCU's assessment emphasizes local communities' participation and the areas' contribution to socioeconomic development, topics scarcely addressed in other tools (TCU, 2021). Instead of grouping management indicators into the macro-processes (context, planning, inputs, processes, products, and results), Indimapa provides individual scores for each indicator, including management plans, participatory management, and biodiversity monitoring. A final average, termed the implementation and management index (hereafter only management index or Indimapa) is then calculated (TCU, 2021). Management assessments typically assume that consolidating management processes results in ecological conservation, yet offer indirect information of conservation status (Geldmann et al., 2021). Indimapa is a continuous variable from zero to three, while human and financial resource indicators are categorical variables classified from zero to three, indicating lower to higher consolidation. These indicators offer insights into team and budget sufficiency for essential management activities (Table S2).

2.3. Statistical analyses

To investigate how the characteristics and context of PAs influence management effectiveness and deforestation rate, we employed structural equation modeling (SEM). This approach allows for the assessment of hypothesized causal relationships among interconnected variables (Lefcheck, 2016). We evaluated the model fit using the chi-square statistic to compare the estimated covariance matrix with the observed one. A good model is indicated by a *p*-value >5 % in the chi-square test, meaning that the estimated covariance matrix does not significantly differ from the observed data (Lefcheck, 2016). Our proposed causal network was designed based on previous studies that examined various relationships embedded within this framework. We hypothesized that the management sphere, management group, external financial support from ARPA, and human and financial resources would have an impact on management effectiveness. The management sphere might influence effectiveness indirectly by determining the availability of resources, staff capacity, and efficiency in executing management actions (Silva et al., 2021). Federal management bodies are typically more focused on PA management, whereas state agencies often face the challenge of overseeing a broader range of environmental responsibilities. We expected ARPA-supported areas to have an indirect effect on management levels through the financial resources provided by the program, as well as a direct effect by implementing management instruments and actions through the program (MMA, 2020).

Sustainable use areas could exhibit lower management effectiveness as they need to balance multiple uses while conserving their territories;

however, their management levels might be higher if they receive community support (Campos-Silva et al., 2021). In contrast, strict protection areas are often established in more remote locations and thus face fewer threats (Nolte et al., 2013). We initially tested the model including the effect of group on management index and deforestation. When this did not yield a good fit, we used "piecewiseSEM" (Lefcheck, 2016) to treat the management group as a random factor, thus removing its effect across all equations and recognizing the limited theoretical support for exploring certain causal relationships in depth. While there is evidence suggesting differences in deforestation rates by management group, these differences appear more related to location factors than to intrinsic group characteristics (Nolte et al., 2013). For management effectiveness, we did not find specific studies addressing this variable.

Regarding deforestation, we anticipated that higher surrounding deforestation would increase pressure, leading to more inner deforestation, even if at lower rates. Additionally, we expected proximity to municipal centers to indicate greater accessibility to PAs, potentially heightening deforestation risks (Hänggli et al., 2023). Management effectiveness is presumed to correlate with ecological outcomes, but disentangling the effect of management from contextual variables that heavily influence deforestation rates is challenging (Coad et al., 2015; Hänggli et al., 2023). Some studies have proposed that deforestation can mobilize resources and protective actions, potentially increasing management scores (Pellin et al., 2022). Alternatively, areas with higher management quality might be located in regions with elevated deforestation pressures, leading to higher deforestation rates (Powlen et al., 2021). This could complicate the accurate quantification of the management effect on deforestation avoidance. By using SEM, we could test the bidirectional relationship between management effectiveness and deforestation and compare model suitability using Akaike's information criterion (AIC). We also specifically examined the resources indicator of the management index, as it has been previously suggested to be a crucial factor for positive ecological outcomes (Geldmann et al., 2018).

In summary, our exogenous variables included the management sphere (federal or state), participation in the Amazon Protected Areas Program (ARPA), and distance to municipal headquarters. The endogenous variables were the percentage of deforestation from 2000 to 2018 within PAs and their surrounding 10 km radius, as well as financial and human resources indicators and the management effectiveness index. We also tested nonlinear relationships involving the area-based variables of external deforestation and distance to municipal centers, by incorporating their squared values into the model.

Data on the management sphere, group, and ARPA participation were obtained from the CNUC (MMA, 2024). We calculated inner and surrounding deforestation using data from the National Institute for Space Research (2000–2018) (INPE, 2024), and assumed this period to be reflective of the management quality recorded in TCU assessments (2018–2019). We obtained the deforestation raster data provided by INPE through the TerraBrasilis platform (accessed in September 2023), originally at a 30-m resolution. To optimize processing, we aggregated the raster cells by a factor of 10 using the modal function, resulting in a coarser-resolution raster. Based on this resampled dataset of 300-m resolution, we calculated the percentage of deforested area within protected areas and their surrounding buffer zones. Data processing and analysis were conducted using the R program (R Core Team, 2024).

2.4. Prioritization for investment in management

The Brazilian Ministry of the Environment (MMA) defined priority areas for meeting conservation targets for the Amazon; however, existing PA were treated uniformly as previously designated "priority" areas, without any further internal ranking or differentiation (MMA, 2021). As a result, newly identified priority areas were restricted to unprotected regions. Our prioritization, in turn, included PAs and complements the priority areas identified by MMA by focusing on defining priority PAs for investment, which is as crucial as the creation of new ones (Adams et al., 2019). We focused on two target groups: endangered species and species for sustainable use. In addition, we included pressure vectors to select areas important for biodiversity threatened by those factors.

Distribution maps of endangered species were derived from "TheMetaLand" Laboratory database at Federal University of Goiás. The modeling protocol is consistent with recent studies focused on conservation applications (Pessoa Da Silva and De Marco Júnior, 2023) and is detailed in Supporting Information (Text S1). Distribution models allow the estimation of species' potential distribution and are particularly useful in poorly sampled regions, such as the Brazilian Amazon, as they enable the extrapolation of information from well-studied sites to broader territories (Pimenta et al., 2022; Pollock et al., 2020). Fifty three out of 147 threatened species met the criterion of having at least 10 % of their distribution in the Amazon biome, all mammals and birds (Fig. S2; Table S3). By applying this threshold, we assume that species with <10 % of their range within the Amazon are likely more dependent on other biomes and have lower ecological relevance to the biome targeted in this study.

The sustainable use species maps come from the database from MMA (2021), accessed in July 2022. It included distribution maps of 20 species: Brazil nut (*Bertholletia excelsa*), nine species of copaiba (*Copaifera* sp.), black caiman (*Melanosuchus niger*), ivory palm (*Phytelephas macrocarpa*), Brazilian mahogany (*Swietenia macrophylla*), piassava palm (*Leopoldinia piassaba*), and six species of turtles: *Kinosternon scorpioides*, *Peltocephalus dumerilianus*, *Podocnemis erythrocephala*, *Podocnemis expansa*, *Podocnemis sextuberculata*, *Podocnemis unifilis* (Fig. S3; Table S3). The species distribution polygons used by the MMA are based on maps published in scientific papers or databases and refined by specialists who participate in workshops to define conservation targets (MMA, 2021). For our prioritization, we rasterized the distribution polygons at a resolution of ~1 km.

We selected the primary drivers of forest degradation in the Amazon, as identified by Lapola et al. (2023): edge effect, timber extraction, fire incidence, and extreme droughts. Lapola et al. (2023) mapped the spatial distribution of these drivers, providing raster data of forest degradation levels caused by each from 2001 to 2018. We adjusted their resolution to ~1 km (Fig. S4). Pressure drivers are often integrated into spatial prioritization as a cost layer, prioritizing areas facing lower pressure (Ribeiro et al., 2018). In our study, we assigned a positive weight aiming to highlight locations requiring increased management actions.

We used Zonation program, version 5 (Moilanen et al., 2022a, 2022b), utilizing the additive benefit function (ABF) to prioritize high average coverage of conservation targets. Zonation iteratively calculates the priority of each cell in the study area using the removal rule, estimating pixel importance based on input data (targets and drivers). This involves sequentially removing cells, starting from those with the lowest conservation value, until it achieves stability of priority ranking. The result is a priority map where each cell is assigned a value from zero to one (Moilanen et al., 2022a). We utilized threat categories from the National List of Endangered Species (MMA Ordinance No. 148/2022) to assign weights to species. Weights were set as 1 for non-threatened, 1.5 for vulnerable (VU), 1.75 for endangered (EN), and 2 for critically endangered (CR) species (Table S3). We adjusted weights by dividing each by the sum of weights and multiplying by the total species count (73). We also adjusted pressure vector's weight to 18.25 to balance importance against species, ensuring a total sum of 73. We ran the program to prioritize the entire Amazon biome, and set up Zonation's area statistics to compute the average priority by PA, inserting a raster in which the cells belonging to each PA were identified by a specific ID.

Finally, we evaluated whether prioritized PAs align with management effectiveness, employing a Pearson correlation test. Additionally, we investigated potential differences in priority level among areas categorized by human and financial resource levels of 0, 1, 2, or 3, which are named here as absent, poor, medium, or high, respectively. Due to non-normal distributions, we utilized the non-parametric Kruskal-Wallis test and Dunn's post-hoc test to adjust *p*-values for multiple paired comparisons.

3. Results

Among the 261 PAs analyzed, 131 are managed by state agencies and 130 by the federal agency (ICMBio). Additionally, 117 participate in ARPA, 77 are designated for strict protection and 183 for sustainable use. Deforestation within a 10 km radius varies from zero to 85 %, with 75 % of the areas below 40 %. Inside PAs, half of areas showed <1.6 % of deforestation, but the maximum value was an extreme of 92 %. The average management effectiveness index is 1.21, with a standard deviation of 0.67 (Fig. S5).

Our structural equation model revealed that all hypothesized pathways were significant, except for the direct effect of distance to municipal seats on inner deforestation, which appeared to act only indirectly through external deforestation (Fig. 1, Table S4). The management sphere negatively impacted both human resources (standard partial effect (β_{std}) = −0.13) and financial resources (β_{std} = −0.40), indicating that state-managed areas have fewer resources compared to federally managed ones. ARPA support had a positive effect on financial resources (β_{std} = 0.35) and the management index (β_{std} = 0.29). Both financial and human resources showed positive associations with the management index (β_{std} = 0.36 and 0.40, respectively). Additionally, the residuals of human and financial resources were positively correlated, suggesting the presence of other variables outside the model influencing both indicators. The management effectiveness index demonstrated a substantial amount of explained variance (R^2 = 0.64), indicating that the included predictors effectively capture factors contributing to the management quality of PAs.

Inner deforestation negatively affected the management index (β_{std} = −0.13), implying that lower deforestation within PAs is associated with higher management quality. Inner deforestation was influenced by surrounding deforestation (β_{std} = 0.67), which itself was impacted by the distance to municipal seats (β_{std} = −0.63). For our model, inner deforestation had a strong level of explained variance (R^2 = 0.50).

We observed a weak negative relationship between the management effectiveness index and inner deforestation (Fig. 2A). Conversely, there was a strong positive correlation between surrounding deforestation and inner deforestation, indicating that high deforestation levels in adjacent areas are strongly linked to increased deforestation within PA boundaries (Fig. 2B). The model did not fit well when testing nonlinear relationships involving external deforestation and distance to municipal seats. An alternative model configuration, where inner deforestation decreases as the management index increases, also showed a good fit. However, a comparison of the two configurations indicated that the pathway from inner deforestation to the management index was more likely than the reverse (AIC = 3114.39 vs. 3119.04).

PAs are distributed across varying priority levels, covering between 1.5 % and 62.7 % of the predicted species distribution area (Table S3). The average priority score for areas was 53 %, with a standard deviation of 27 %. Among the 65 areas with a high priority score (>72 %), 62 % had medium or poor management effectiveness (<1.57), and only 5.7 % exhibited high management effectiveness (> 2) (Fig. 3, areas classified in priority 4). The Sustainable Development Reserve Mamirauá and the Biological Reserve of Gurupi are examples of high priority areas with a high management index (class 4–4, Table S5). Notably, 25 areas are of particular concern due to their high priority and very low management effectiveness (priority 4 and management index 1 in Fig. 3), like the Environmental Protection Area Triunfo do Xingu and the National Park of Pico da Neblina.

The correlation between priority degree, obtained with Zonation, and the management effectiveness index is slightly negative, indicating a small tendency for management index to decrease as priority increases (r = −0.16; p < .05; Fig. S6). Similarly, areas with poor technical and financial resources had a higher average priority compared to other areas (Fig. S7), according to Kruskall-Wallis tests (p < .001). Significance was observed between human resource levels 0 and 2, 0 and 3, 1 and 2, and 1 and 3, as well as between financial resource levels 0 and 2, and 0 and 3.

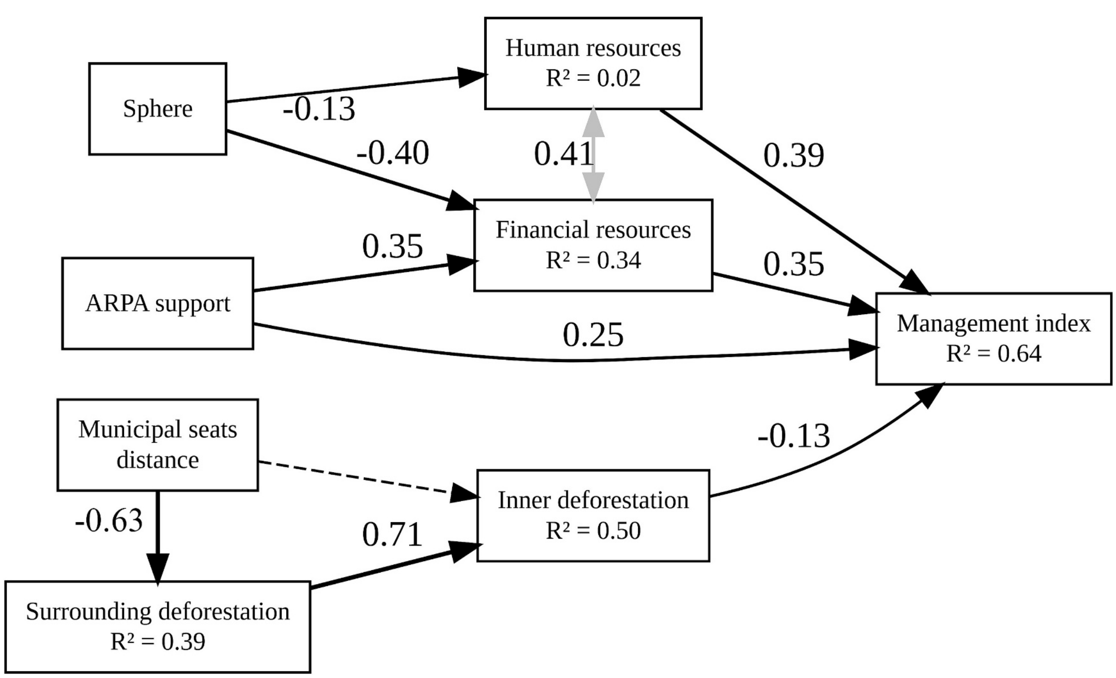

Fig. 1. Structural equation model with good fit, showing the relationships between factors influencing management and deforestation outcomes in protected areas ($X^2_{(14)}$ = 15.77, p = .328). Standardized path coefficients are displayed along each pathway, and R^2 values represent the variance explained for each endogenous variable. Solid arrows represent significant effects (p < .05), dashed arrows represent non-significant effects ($p \geq$ .05), and the gray arrow represent an estimated correlated error. For the management sphere, the "federal" category was used as the reference compared to the "state" category, and for ARPA support, "no support" was used as the reference.

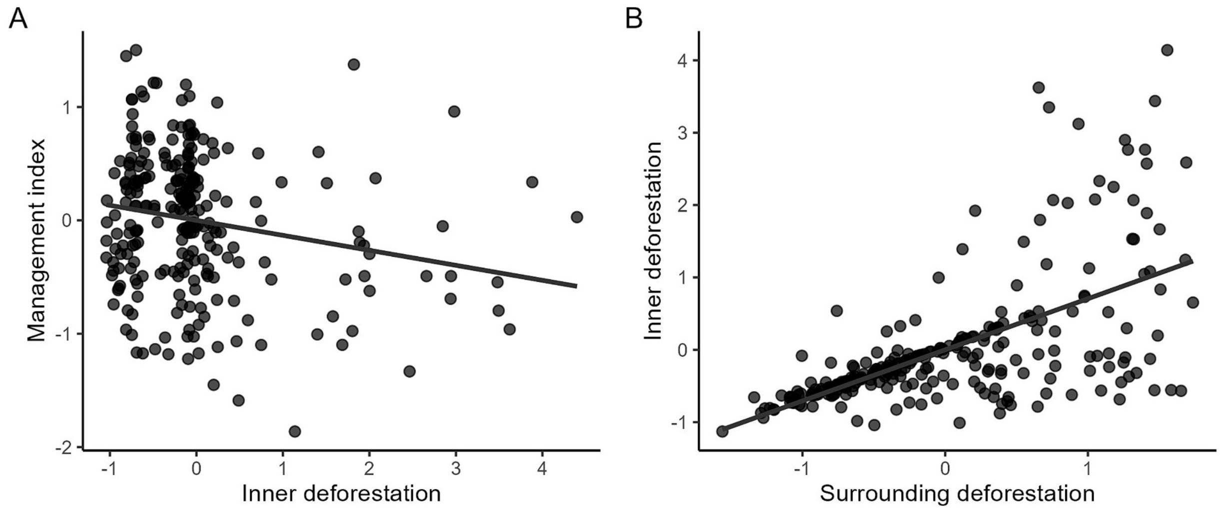

Fig. 2. Partial residual plots illustrating the relationship between inner deforestation and two variables: (A) management effectiveness index, showing a slight negative association with inner deforestation; and (B) surrounding deforestation, indicating a strong positive association with inner deforestation.

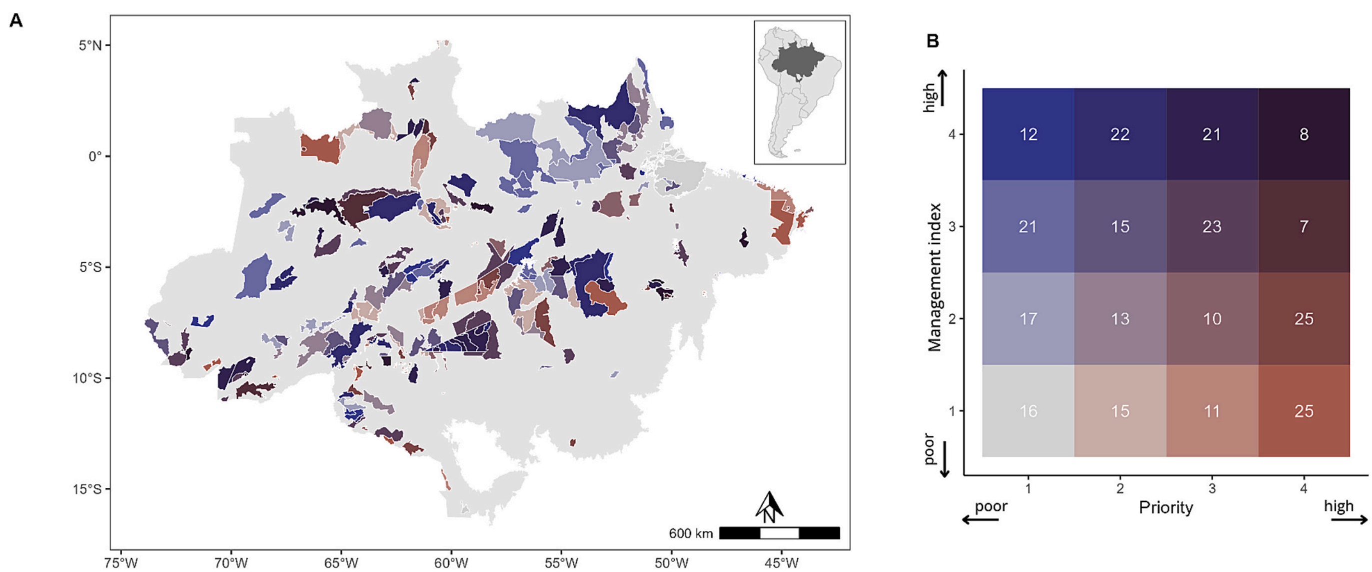

Fig. 3. (A) Bivariate map and (B) frequency chart of protected areas in each combination class between the management effectiveness index and priority for conservation degree. Classes and colors were defined by quartiles, that is, Management index = 1 and Priority = 1 are the units that are among the lowest 25 % in priority and management effectiveness index.

4. Discussion

The Amazon hosts the largest extent of PAs in Brazil, playing a critical role in combating deforestation (Alves-Pinto et al., 2022), despite of varying greatly in their administrative structure. Our findings highlight that areas without ARPA support, managed by state agencies, or located in more deforested regions exhibit lower management effectiveness. Resource availability is a significant challenge, with state-managed areas and those lacking ARPA support perceiving a greater insufficiency of resources. While detailed data on individual investments would be beneficial, current evidence points to a clear disparity between PA expansion and resource allocation (Silva et al., 2021; TCU, 2021). Silva et al. (2021) identified a financial deficit in all federal PAs in the Amazon, and the TCU evaluation shows that the perception of inadequate resources is higher in state-PA than in federal ones. Our analysis further demonstrates that this inadequacy negatively affects management effectiveness.

The ARPA initiative, the world's largest tropical forest conservation program, began in 2002 and facilitated the establishment of 46 PAs by 2010, spanning over 24 million hectares (MMA, 2020). Beyond the creation of new PAs, ARPA supports the implementation of essential management tools, including the formation of management councils and biodiversity monitoring. Over the past two decades, ARPA-supported areas have shown a significant reduction in deforestation rates, preventing up to 39 % of the deforestation that would have occurred without such support (Soares-Filho et al., 2023). This success is attributed to ARPA's strategic allocation of resources to enhance management practices, thus reinforcing the relationship between consolidated management and deforestation prevention.

Our study found a weak negative correlation between deforestation within PAs and management effectiveness, contrasting with findings from Mexico where higher management levels were observed in more pressured regions but still maintained better forest cover (Powlen et al., 2021). A global analysis similarly noted that PA with higher population densities—indicative of anthropogenic pressure—experienced improved management over time (Geldmann et al., 2015). Conversely, a study in the Brazilian Amazon has reported no direct link between deforestation and management effectiveness (Pellin et al., 2022) suggesting that management resources may be allocated to less impacted areas or that management efforts may be constrained by governance limitations. Another hypothesis is that deforestation and low management levels result from weakened environmental policies, known to control native vegetation loss trends (Shah et al., 2021). Here, we applied SEM to investigate the complex interrelationships between management and the broader context in which PA are situated. This approach allowed us to test multiple pathways simultaneously; however, we faced two main challenges. First, the lack of theoretical guidance on specific aspects, such as differences in the management effectiveness of strictly protected areas versus sustainable use areas. Second, SEM itself poses methodological constraints, as increasing the number of variables and relationships can hinder model fit (Lefcheck, 2016). We therefore prioritized parsimony, opting for the simplest model that retained explanatory power. Nonetheless, we highlight the importance of future studies that focus specifically on the determinants of management quality and outcomes, and on expanding the coverage of effectiveness assessments to enable the testing of more comprehensive models with larger datasets.

Strategically directing resources to PA management is crucial for enhancing their conservation impact. Despite a weak overall association, our results indicate that priority areas tend to have lower management, financial, and human resources. Historical investment patterns in PAs often aligned with regions experiencing higher deforestation, greater species diversity, and a higher number of threatened species (Qin et al., 2023). However, recent shifts in priorities, with a focus on carbon storage and climate concerns over biodiversity, may be associated to our findings (Qin et al., 2023). Ensuring that high-value biodiversity areas receive adequate management resources is essential for preventing biodiversity loss, particularly under high anthropogenic pressure (Schleicher et al., 2019).

This study offers a systematic conservation planning strategy for guiding investment decisions, considering available data. Conserving threatened mammals and birds and sustainably used species aligns with Brazil's obligations under the Convention on Biological Diversity (CDB), and with the main goals of the National System of Conservation Units (SNUC). However, individual PAs may have distinct goals, such as preserving unique geomorphological features or safeguarding water sources. Thus, while this analysis suggests a system-wide strategy focused on specific targets, local management decisions may align more closely with specific area contexts and objectives.

Effectively and equitably managed protected areas generate multiple benefits beyond biodiversity conservation, including supporting the way of life of traditional peoples and communities, promoting ecosystem services, and preserving cultural heritage sites (Naidoo et al., 2019; Zhang et al., 2023). Our objective was not to account for all possible scenarios, but to highlight the urgent need to halt the loss of threatened species in areas under intense pressure. Nonetheless, we incorporated sustainable use targets to help identify areas where overlapping objectives could be achieved across all selected conservation targets. Still, we acknowledge that any prioritization is inherently influenced by the choice of targets, and we emphasize the need for further studies that explore aspects not addressed in our analysis, as our study complements the Brazilian Ministry of the Environment (MMA) prioritization by ranking PAs. Lopes Dias et al. (2024), for example, proposed an categorization matrix to identify context-specific actions for Amazon sustainable-use PA, focusing on supporting local communities. Despite the potential for complementarity between conservation and other agendas, there is a growing tendency to sideline biodiversity conservation in favor of more politically appealing priorities, such as directing funding primarily toward areas with higher carbon stocks (Qin et al., 2023). Our study highlights the resulting investment gap in high-pressure areas critical for species conservation.

Data quality in prioritization is hampered by biases in knowledge about Amazonian species, favoring certain taxonomic groups and accessible regions (Carvalho et al., 2023). Over half of the upland areas in the Amazon remain poorly studied, particularly those within indigenous lands and more conserved regions (Carvalho et al., 2023). To address this reality, we used both a global occurrence database and a Brazilian database managed by the federal agency responsible for managing conservation units (ICMBio, 2023). The latter is the result of a coordinated governmental effort, developed in partnership with several experts, and supports the elaboration of the official national list of threatened species (ICMBio, 2023). Deficiencies and spatial biases in data collection can be addressed through the use of appropriate species distribution models, as employed in this study (Pollock et al., 2020). Moreover, such models enable large-scale decision-making across multiple taxa simultaneously (De Marco et al., 2023; Pimenta et al., 2022).

Although we modeled the distribution of all threatened vertebrates, amphibians and reptiles were ultimately not included in our sample because all species in these groups had <10 % of their predicted distribution within the Amazon. This suggests that the most threatened species in these taxa are likely more dependent on other biomes. Given that the most heavily sampled areas in the Amazon also correspond to those under greatest anthropogenic pressure (Carvalho et al., 2023), the aforementioned data gap may not significantly affect the representativeness of our conservation targets. Threatened species are expected to be more concentrated in degraded areas, precisely because such conditions increase their risk. However, our modeling protocol excludes species with fewer than five occurrence records, which likely led to the omission of extremely rare species that may persist in poorly sampled regions. This highlights the importance of broad, long-term biodiversity monitoring initiatives, such as ICMBio's Biodiversity Monitoring Program (Monitora et al., 2021), which is specifically implemented within protected areas. As such programs are consolidated, we expect improvements in data availability and, consequently, in the quality of future conservation analyses. Hence, our study focused on management investments, especially for threatened mammals, birds and sustainable-use species conservation, while we stress the importance of concerted efforts to enhance research in conserved biome areas, minimizing sampling gaps and enabling informed planning and action (Johnson et al., 2024).

Another limitation of this study concerns the availability of data on management effectiveness. We relied on the most recent assessment conducted by the Brazilian Federal Court of Accounts (TCU), as it remains the only evaluation that covers all protected areas in the Brazilian Amazon. Although the data are not current, it is well known that, at the system level, changes in protected area management tend to occur slowly and gradually (Geldmann et al., 2015). Therefore, while localized shifts may have taken place, it is likely that the overall pattern has remained relatively stable, particularly in the Amazon, where chronic underinvestment in PA management persists (Silva et al., 2021). Nonetheless, we emphasize the urgent need for regular, comprehensive, and long-term assessments. In this context, ICMBio has been advancing the Management Analysis and Monitoring System (SAMGe). Although SAMGe currently includes a greater number of federal areas and has not yet achieved full coverage of the Amazon region, it is a dynamic and ongoing initiative that holds great potential to inform and strengthen public policies for protected area management. Moreover, there is a lack of systematic data on social organization and community participation which need to be addressed to design evidence-based initiatives (Lopes Dias et al., 2024).

The estimated minimum annual cost to conserve around 80 % of the Amazon for ecological integrity maintenance ranges from $1.7 to $2.8 billion (Silva et al., 2022). This includes expenses for managing protected areas and indigenous lands covering 3.5 million km^2 (Silva et al., 2022). For Brazilian federal PAs alone, the projected annual cost is $341 million, yet public expenditure in 2016 amounted to only 11 % of this sum (Silva et al., 2021). This highlights the scale of the challenge, which could be met through transnational cooperation, as exemplified by

ARPA, emphasizing transparency and efficiency. Currently, 114 protected areas are benefiting from the Program, with an estimated investment of $280 million from 2014 to 2019 (MMA, 2020). These initiatives should complement public spending and prioritize areas with higher biodiversity value, as well as those experiencing greater pressure or administrative deficiencies, based on the gaps identified in our analysis. Additionally, conserving the biome necessitates other strategies, including enforcement, combating illegal practices, and promoting sustainable landscape management. The urgency and scale of the challenge demand swift and effective action, grounded in both science and social justice.

CRediT authorship contribution statement

Letícia Lopes Dias: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Bruno Roberto Ribeiro:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Angela Pellin:** Writing – review & editing. **Fabiana Prado:** Writing – review & editing, Project administration, Funding acquisition. **Neluce Soares:** Writing – review & editing, Project administration. **Paulo De Marco Junior:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Leticia Lopes Dias reports financial support was provided by Brazilian Economic and Social Development Bank. Leticia Lopes Dias reports financial support was provided by Gordon and Betty Moore Foundation. The other 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.biocon.2025.111303.

Data availability

Data and code can be accessed through the GitHub repository.

Dataset for management and priorities for biodiversity conservation in Amazon protected areas (Original data) (github)

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