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Effectiveness of protected areas in containing the loss of Peruvian Amazonian forests

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ABSTRACT

Peruvian Amazonian Forests (PAF), vital for biodiversity, climate, and human well-being, lost 2.92M ha during 2001–2022, mainly due to anthropogenic activities. This prompted strategies to conserve and protect the PAF, such as land use and natural resource restrictions, with natural protected areas (NPAs) being the main strategy. This study evaluated the effectiveness of 41 NPAs in containing deforestation in the PAF by analyzing national spatial data. An Effectiveness Index (EI) was constructed by adding five standardized parameters: (1) the percentage of deforested area (DA%) and (2) its annual rate of change (DAr) between 2000 and 2022 inside each NPA, (3) the difference in DAr between NPAs and their surrounding areas, (4) their corresponding ecoregions, and (5) the entire PAF. In 2000, the DA% was 7.15 % of the PAF, increasing to 10.88 % in 2022. NPAs showed lower DAr than their surrounding areas and ecoregions, except for five NPAs. Of the 41 NPAs, nine were non-effective (EI≤3), 31 moderately effective (3<EI<4), and only one effective (EI≥4). Indirect-use NPAs (strict with integral protection) were slightly more effective than direct-use NPAs (where sustainable use is allowed). Among national categories, the 11 National Parks, equivalent to IUCN Category II, had the highest average EI (3.414). In general, NPAs have shown moderate effective in containing deforestation, and require risk-specific mitigation strategies, especially in NPAs with low DA% but high DAr. Finally, a quantitative and systematic assessment tool is provided, which can improve the formulation of strategies to mitigate deforestation and preserve crucial ecosystem services in PAF.

1. Introduction

Amazon forests are key to biodiversity conservation and climate change mitigation, providing habitat for multiple species, storing carbon, and providing various ecosystem services (Borma et al., 2022; Koh et al., 2021). The Peruvian Amazonian forests (PAF) represent the second-largest portion of the Amazon rainforest in Latin America and the fourth-largest tropical forest area globally, with a complex heterogeneous landscape and various anthropogenic pressures that have increased deforestation in the last decade (Rojas et al., 2021). As a result, 2.92M ha of forest were lost during 2001–2022 (MINAM, 2024a), due to logging and mining (legal and illegal), cattle ranching, oil extraction, and agriculture, facilitated by road infrastructure (Cruz et al., 2023; Móstiga et al., 2024a). This has led to the design of strategies to conserve and protect forests, such as land use and natural resource use/extraction restrictions, with natural protected areas (NPAs) being the main strategy (Rico-Straffon et al., 2022). The conservation objectives and goals of the NPAs range from biological, geological, and economic to socio-cultural and heritage (Maxwell et al., 2020). Therefore, NPAs can be strictly protected, prohibiting resource extraction and environmental modifications, or allow certain activities under approved management plans.

In Peru, 17.9 % (23M ha) of the land surface is protected by the National System of Natural Areas Protected by the State (SINANPE),

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under the regulation of the National Service of Natural Protected Areas (SERNANP, 2024a, 2024b), an agency of the Ministry of the Environment (MINAM). SINANPE fulfills its protective role for PAF and achieves lower deforestation rates than areas without NPAs (Cotrina-Sánchez et al., 2021a; Dourojeanni, 2023; Móstiga et al., 2024b). However, NPAs still face deterioration processes ranging from resource extraction to ecosystem transformation, whose magnitude depends on management, history, socioeconomic context, resource use conflicts, community participation, management institutions, and ecosystem vulnerability influenced by climate, topography, and vegetation (Cruz et al., 2023; Figueroa et al., 2011). Therefore, the evaluation of the capacity or effectiveness of NPAs to meet their conservation objectives has become a relevant concern (Maxwell et al., 2020). Beyond comparing deforestation rates between NPAs and non-NPA areas, as done in previous studies, it is crucial to establish a robust effectiveness indicator for a more comprehensive assessment.

There are three perspectives for evaluating the effectiveness of NPAs: design, management, and ecological integrity (Hockings et al., 2006; Lee and Abdullah, 2019). Currently, the evaluation of NPAs is mainly focused on the management (Lee and Abdullah, 2019), and SERNANP (2022) has adopted the Management Effectiveness Tracking Tool (METT) (Stolton et al., 2007). From an ecological perspective, SERNANP (2024c) evaluates the Conservation Status (CS) of NPAs using a grid-based system that identifies four effects caused by 12 predefined anthropogenic activities, expressing EC as the percentage of unaffected grids. Although a high correlation between NPA management (METT) and ecosystem conservation (CS) would be expected, a very low correlation ($r = 0.1054$) was found, likely due to METT's self-assessment nature, which can bias results, its focus on intermediate management processes rather than conservation outcomes, and CS's limitation in fully capturing ecological integrity (Arenas and Cortez, 2023). Given these limitations, complementary approaches are needed to better capture ecological effectiveness, such as those based on changes in Land Use/Land Cover (LULC).

LULC changes are commonly used to assess ecological integrity due to their global magnitude and their relationship with other degradation processes, such as biodiversity loss, climate change, land degradation, and loss of ecosystem services (Aguilar et al., 2020; Kubacka et al., 2022). In Peru, multiple studies have analyzed deforestation in NPAs and their surrounding areas (Cotrina-Sánchez et al., 2021a; Dourojeanni, 2015; Móstiga et al., 2024b). MINAM (2024a) has also assessed deforestation in PAF annually since 2000. However, it has not yet been translated into an ecological Effectiveness Index (EI), such as the one previously developed and applied to multiple NPAs in Mexico (Sánchez-Cordero et al. 2007; Figueroa and Sánchez-Cordero 2008; Figueroa et al., 2009, 2011). Recently, EI was applied to 18 federal NPAs in Mexico (Aguilar et al., 2020) and four private-communal NPAs in northern Peru (Delgado et al., 2021). The EI is calculated using DA% and DAr for each NPA, with DAr compared across their geographic contexts (surrounding area and ecoregion). While this approach has been valuable, its reliance on binary values for certain parameters oversimplifies variability among NPAs (Figueroa et al., 2011). This study proposes standardized scores for all parameters, enabling a more precise and comprehensive evaluation of effectiveness.

This study evaluated the effectiveness of 41 NPAs in containing the loss of PAF. The evaluation included: (i) a diagnosis of the deforested area and rate of change of this area between 2000 and 2022, (ii) a comparative analysis of rates of change between NPAs and their geographic contexts (surrounding areas, ecoregions, and the entire PAF), (iii) construction of an effectiveness index based on the previous analyses, and (iv) an analysis of the relationship between the constructed EI and the tools used by SERNANP (METT and CS). The purpose of the study is to contribute to the conceptualization of monitoring in the NPAs (WCS, 2020) and the current effectiveness evaluation tools (SERNANP, 2024c, 2022).

2. Material and methods

2.1. Study area

The study area is confined to the PAF boundary (78 308 801 ha) (Fig. 1a–b), a polygon developed by MINAM to annually monitor the area of Forest and Non-Forest from a 2000 baseline (Vargas et al., 2016a) (Fig. 1c). The PAF area ranges from 40 to 4400 m.a.s.l and overlaps 15 of 21 ecoregions that SERNANP (2024a) uses to evaluate the representativeness of the conservation of the NPAs (CDC-UNALM, 2006). Forty-one publicly administered NPAs were selected, which had more than 70 % of their area within PAF and were decreed before 2017. The latter is because the most recent LULC map is from 2022 (MINAM, 2024b), and it is assumed that five years are sufficient to detect the effect of NPAs on LULC changes (Aguilar et al., 2020; Figueroa and Sánchez-Cordero, 2008). In practice, there were no NPAs enacted in 2016 and 2017 (Fig. 1d).

The selected NPAs belong to six definitive SINANPE categories, Protected Forest (BP, $n = 2$), National Park (PN, $n = 11$), Communal Reserve (RC, $n = 10$), National Reserve (RN, $n = 5$), National Sanctuary (SN, $n = 4$) and Regional Conservation Area (ACR, $n = 6$). Also included were three Reserved Zones (ZR), NPAs with transitory status that require further studies to determine, among other aspects, their extension and definitive category. The six definitive categories are classified into indirect use NPAs (PN and SN), which are dedicated to integral protection, prohibit resource extraction and environmental modifications; and direct use NPAs (ACR, BP, RC, and RN), which allow resource exploitation and extraction, mainly by local populations, under management plans (SERNANP and SPDA, 2011). In these direct use NPAs, permitted activities include agriculture, timber harvesting, non-timber forest product collection, and regulated tourism activities. However, certain land uses, such as intensive agriculture (Dourojeanni, 2022; Sierra, 2021) or large-scale timber harvesting (Finer et al., 2020; Villa and Finer, 2019), may pose a higher risk of deforestation if not adequately monitored and managed. Of all the NPAs analyzed, only the ACR is not administered by SERNANP; it is managed by the regional governments due to its status as a regional NPA.

On the other hand, regarding the International Union for Conservation of Nature (IUCN) categories, 11 NPAs belong to Category II - Ecosystem protection and recreation (corresponding to the 11 PN), 4 NPAs to Category III - Conservation of unique natural features (corresponding to the 4 SN), 17 NPAs to Category VI - Sustainable use of natural resources (includes BP, RC, and RN), and 9 NPAs do not have an assigned category (includes ACR and ZR) (Fig. 1d).

2.2. Methodological process and spatial database

Fig. 2 shows the four-step methodological process for estimating the Effectiveness Index (EI) of NPAs. The NPAs boundaries were downloaded from the GEOANP Viewer (SERNANP, 2024a), and for each NPA a surrounding area (i.e., buffer) of equivalent size was generated (Delgado et al., 2021; Figueroa et al., 2009; Figueroa and Sánchez-Cordero, 2008). Various buffer sizes were tested in ArcGIS Pro 3.x for each NPA until an equivalent surface area buffer was identified. The area covered by other NPAs (whether included in the analysis) and the territory of other countries were excluded (Sánchez-Cordero et al., 2007). The map of forest/non-forest 2000 and annual forest loss from 2001 to 2022 was obtained from the GEOBOSQUES Platform (MINAM, 2024b). Methodological protocols for forest detection and forest loss are detailed in MINAM (2021) and Vargas et al. (2016b). The ecoregion map (SERNANP, 2024b) was provided by SERNANP.

2.3. Estimate of the percentage and rate of change in the deforested area

The percentage of deforested area (DA%) was calculated separately for each NPA, surrounding area, ecoregion, and the entire PAF. The

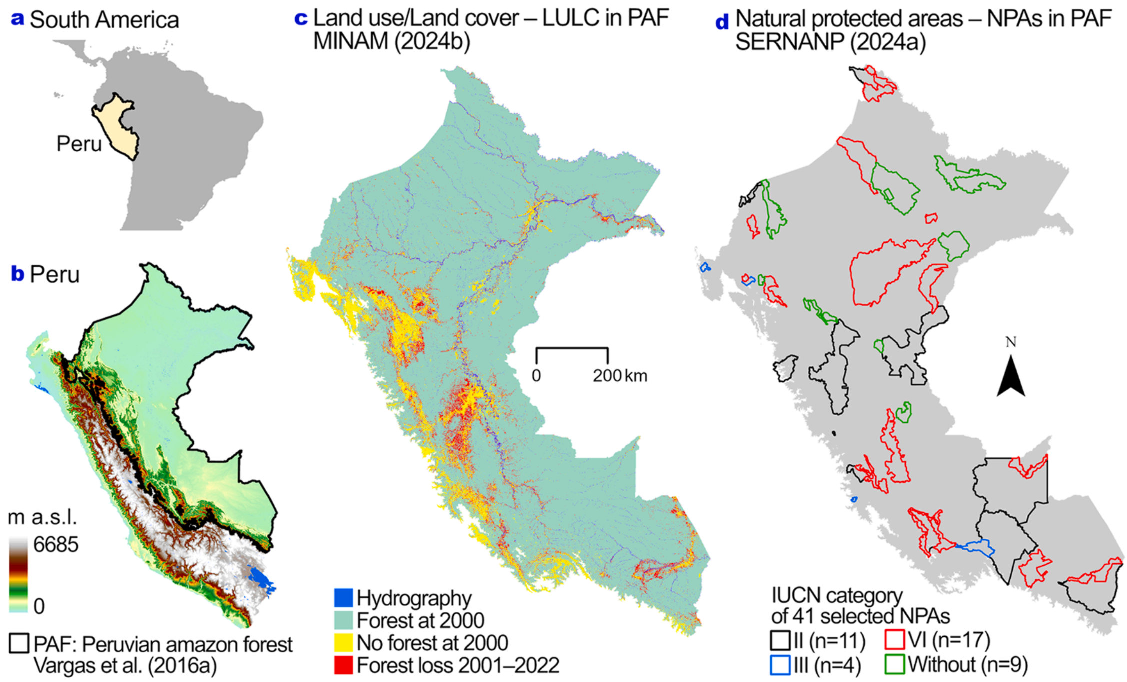

Fig. 1. Location, forest, loss of forests and natural protected areas (NPAs) selected in the Peruvian Amazon Rainforest (PAF).

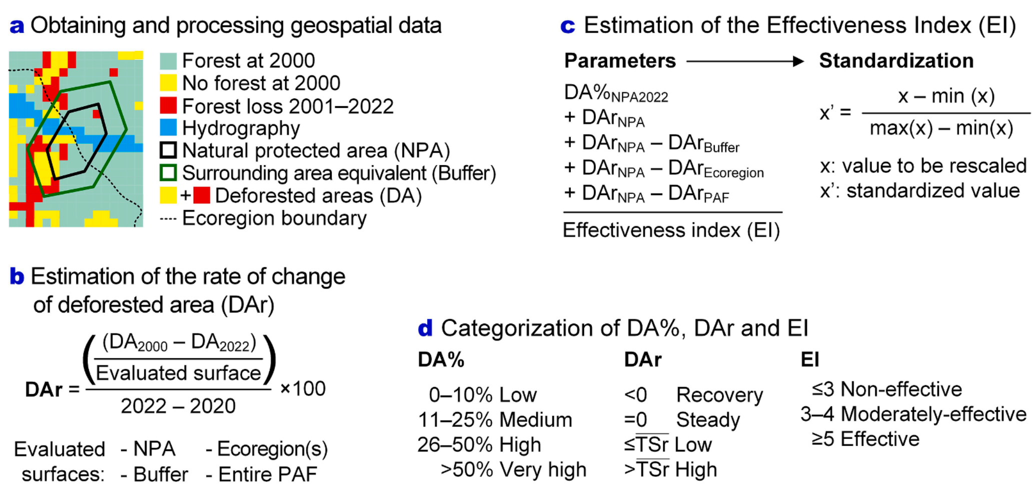

Fig. 2. Methodological process for estimating the Effectiveness Index (EI) of NPAs.

deforested areas (DA) were the No Forest in 2000 and Forest loss 2001–2022 polygons on the GEOBOSQUES map (MINAM, 2024b) (Figs. 1c and 2a), corresponding to areas with anthropogenic intervention such as agriculture, livestock farming, human settlements, and roads (detailed definition of the legend at Vargas et al., 2016a). In addition, the rate of change of deforested area (DAr) was calculated as the percentage of NPA that has been transformed annually, on average, during the study period (Aguilar et al., 2020) (Fig. 2b). For certain NPAs, the GIS-based area, derived from spatial analysis, differs from the legal area recognized by SERNANP (2024a). In such cases, the GIS area was used as the total area of the PNA for calculations, ensuring consistency with the spatial data analyzed.

The NPAs were classified according to DA% and DAr (Figueroa et al., 2011). DA% was classified as low (0–10 %), medium (11–25 %), high (26–50 %) and very high (>50 %); and the DAr as recovery (DAr < 0, i.e., vegetation cover was recovered), steady (no change, DAr = 0), low (0 < DAr < $\overline{\text{DAr}}$ of the analyzed NPAs) and high (DAr > $\overline{\text{DAr}}$ of the analyzed NPAs).

2.4. Estimation of the effectiveness index (EI)

An EI was calculated based on DA% and DAr for each NPA, with DAr compared across three geographic contexts: surrounding area, ecoregion, and entire PAF (Figueroa et al., 2011; Sánchez-Cordero et al., 2007) (Fig. 2c). The main differences in the estimation of EI in previous studies were (i) the contexts of comparison of LULC processes (i.e., DAr) relative to those within the NPA, which influenced (ii) the number of parameters used (from three to five) (Figueroa et al., 2011, 2009; Figueroa and Sánchez-Cordero, 2008; Sánchez-Cordero et al., 2007). As context, DAr within NPAs were compared with surrounding areas of equal size for all NPAs or surrounding areas with equivalent surface area for each NPA; as well as with the ecoregion or to the political boundary in which the NPA is located.

On the one hand, using surrounding areas of standardized size causes the evaluation method to differ for small and large NPAs (i.e., small NPAs are compared with proportionally larger areas, while large NPAs are contrasted with proportionally smaller areas) (Figueroa et al., 2011).

Therefore, LULC processes should be compared with surrounding areas of equivalent size to each NPA (Delgado et al., 2021). For this reason, the official buffer zones established for certain NPAs were not used in this study, as they are not proportional to their NPA and differ in size between NPAs. On the other hand, LULC processes in NPAs should be analyzed concerning the ecoregions in which they are located, and not in terms of political boundaries, since within each ecoregion there are shared environmental and agricultural production characteristics that affect LULC processes (Figueroa et al., 2011). SERNANP (2024a) has a map of 21 terrestrial ecoregions with which it evaluates the representativeness of conservation in Peru (CDC-UNALM, 2006), and as in this study, it can also be the framework for comparison of the LULC processes of the NPAs.

For each NPA, the five parameters considered were: 1) DA% within the NPA in 2022; 2) DAr in the NPA (2000–2022); 3) difference between DAr in the NPA and that estimated in its surrounding area, 4) difference between DAr in the NPA and that estimated in their respective ecoregion, and 5) difference between DAr in the NPA and that estimated in the entire PAF. When the NPAs coincided with two or more ecoregions, a weighted rate was calculated, where the percentages of the NPA corresponding to each ecoregion functioned as weighting values (Sánchez-Cordero et al., 2007). For the last three parameters, positive difference values (i.e., DAr in the NPAs greater than in the comparison areas) took on a value of 0, the others were standardized. Data for each of the five parameters were standardized to values between 0 and 1 with the simplest method of scaling characteristics to independent variables (Aguilar et al., 2020) (Fig. 2c). The sum of standardized parameters generates the EI, therefore, it can take values between 0 and 5. NPAs with an EI close to 0 are of low effectiveness, while NPAs with an EI close to 5 would be the most effective of the set of NPAs analyzed. In addition, three categories of effectiveness were assigned to the NPAs (Figueroa and Sánchez-Cordero, 2008): effective (EI≥4), moderately-effective (3<EI<4), y non-effective (EI≤3).

2.5. Comparative analysis of indices and tools

In previous studies, the EI is influenced by the binary score, as the last three comparisons (parameters) only take on values of 0 or 1: when the NPA presents an increase in DA greater than its respective surrounding area or ecoregion, it acquires a value of 0 (negative positive); otherwise, it acquires a value of 1 (negative difference) (Figueroa et al., 2011). However, this study modified that approach since it was considered that an NPA with a difference of −0.6146 (RN09) in DAr for its surrounding area, cannot be scored equally with another NPA that has a difference of −0.0007 (PN13). The score was standardized to values between 0 and1 as the first two EI parameters, and RN09 scored 1 while PN13 scored 0.003. Both standardized and binary EI were calculated to evaluate their influence on the classification results of NPA effectiveness.

SERNANP (2022) has adopted the Management Effectiveness Tracking Tool (METT) (Stolton et al., 2007), which comprises 30 questions scored on three dimensions (design and planning, adequate management processes and systems, meeting objectives) and determines percentage management levels for each NPA as no or minimal progress (0–32 %), some progress (33–52 %), important progress (53–82 %), optimal progress (83–99 %), and maximum progress (100 %). The average METT of 76 NPAs administered by SERNANP was 47.57 % in 2016 and increased to 60.19–64.60 % in 2019–2022 (Arenas and Cortez, 2023). In addition, SERNANP (2024c) estimates the Conservation Status (CS), which comprises the grid of each NPA and the identification of four effects (habitat loss, overuse of resources, pollution, displacement of native species by introduction of exotic species) generated by 12 predefined frequent anthropogenic activities (SERNANP, 2014). The CS of each NPA is 100 % minus the percentage of affectation, which is the number of grids with effects over the total number of grids. The average CS for 2016 and 2019–2022 remained between 95.92–96 % (Arenas and Cortez, 2023). The correlation between EI and SERNANP's tools (METT and CS) was calculated to assess their relationship and consistency in evaluating NPA effectiveness.

3. Results

3.1. Percentage and rate of change in deforested area

In 2000, the deforested area (DA) comprised 7.15 % (55,956.56 km^2) of the PAF territory; during 2001–2022, 29,212.43 km^2 of Amazonian forests were lost, and the DA increased to 10.88 % (85,168.99 km^2) in 2022, at an annual rate of change (DAr) of 0.1696 %. This DAr was higher than the DAr of 93 % of NPAs analyzed, while it was exceeded by the DAr of three NPAs: BP04 'San Matías-San Carlos Protected Forest', BP06 'Alto Mayo Protected Forest' and RC01 'Yanesha Communal Reserve' (Fig. 3). The average DAr of the NPAs was 0.0399 %, 27 (66 %) of the 41 NPAs have below average DAr, 0.0008 % is the minimum DAr (PN13) and 0.2030 % the maximum DAr (BP06). The indirect use NPAs (PN and SN) presented a lower average DAr than the direct use NPAs (BP, RC, RN and ACR), with averages of 0.0262 and 0.0499 (difference of −0.0238 %), respectively. This difference is reversed when looking at the medians of 0.0247 and 0.0117 (difference of 0.0130 %).

In the surrounding areas (buffers) of the NPAs, the average DAr was 0.1699 %, with a minimum of 0.0014 % (corresponding to PN13) and a maximum of 0.6521 % (corresponding to RN09). The DAr of the PAF territory (0.1696 %) was exceeded by the surrounding areas of 15 NPAs (Fig. 3). The NPAs presented lower DAr than in their respective surrounding areas, except for RC08 'Chayu Nain Communal Reserve', which presented an DAr 0.0015 % higher than in its surrounding area. The NPAs presented lower DAr than in their respective ecoregions, except for ACR06 'Imiría Regional Conservation Area', which presented an DAr 0.0079 % higher than in its ecoregion.

Different levels of conservation of the PAF were found, from those NPAs where DA<0.5 % was observed in 2022 (15 NPAs, 37 %), to the NPAs that showed DA>10 % (PN02 'Tingo Maria National Park' and ACR06). The average DA% of the analyzed NPAs was 3.4 %, 27 (66 %) of the 41 NPAs have below average DA%, 0.08 % is the minimum DA% (ACR 04 'Tamshiyacu Tahuayo Communal Regional Conservation Area'), and 26.4 % the maximum DA% (ACR06). Due to the LULC change processes that occurred during 2000–2022, a reduction in the number of NPAs with low DA% (<1 % and 1–3 %) was observed, while the number of NPAs with higher DA% (3–5 % and 5–10 %) increased (Fig. 4a).

DA% depends on the extension of each NPA, so it is necessary to consider its net area. In the net area, the average DA of the analyzed NPAs increased from 5802.20 ha in 2000 to 8001.51 ha in 2022, with ZR07 'Sierra del Divisor Reserved Zone' (16.65 ha and 72.37 ha) and RN08 'Pacaya-Samiria National Reserve' (78,068.41 ha and 88,362.03 ha) being the NPAs with the lowest and highest net DA, respectively. During 2001–2022 all NPAs experienced loss of their PAF, 2199.31 ha was the average loss, 34.56 ha was the minimum loss (in PN13), and 11,457.53 ha was the maximum loss (in RC02 'El Sira Communal Reserve'). In 2022, 25 (61 %) of the 41 NPAs had >1000 ha transformed, and the NPAs with the maximum extreme of DA (>10,000 ha) went from five NPAs in 2000 to nine NPAs in 2022 (Fig. 4b).

NPAs with a low DA% in 2022 (<10 %) formed two groups (Table 1). In the first group of 27 NPAs, DA increased with a lower-than-average DAr, and certain NPAs, although sharing low DAr, showed a contrasting net change in DA, such as PN13 (1.57 ha/yr) and RN08 (467.89 ha/yr). The second group of 12 NPAs had a high DAr between 2000 and 2022 (i.e., higher than average DAr), and certain NPAs showed a contrasting net change in DA, as is the case of SN08 'Tabaconas-Namballe National Sanctuary' (15.70 ha/year) and RC02 (520.80 ha/year). PN02 had a medium DA% (between 10 and 25 %) while presenting a high DAr. The NPA with a high DA% (between 25 and 50 %) and high DAr was ACR06. It was observed that NPAs classified in the groups with high DAr

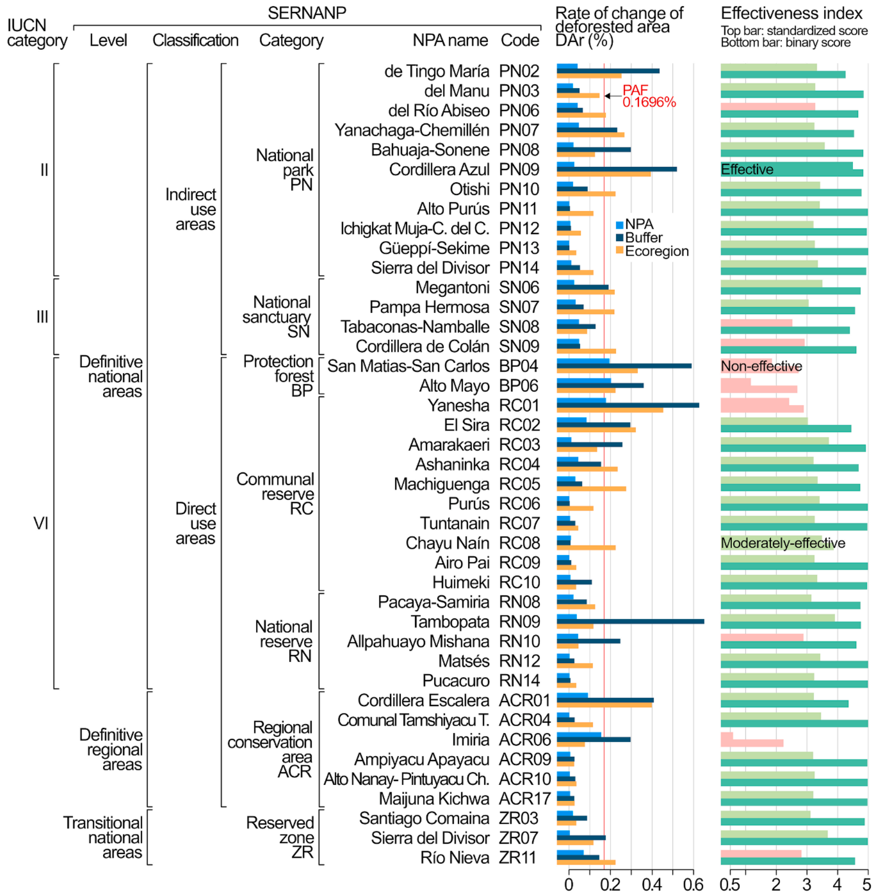

Fig. 3. Rate of change of deforested area (DAr) during 2000–2022 in natural protected areas (NPAs), their surrounding areas (Buffer), ecoregions, and the Peruvian Amazon Forest (PAF), and values of the standardized and binary effectiveness index (EI) for each NPA.

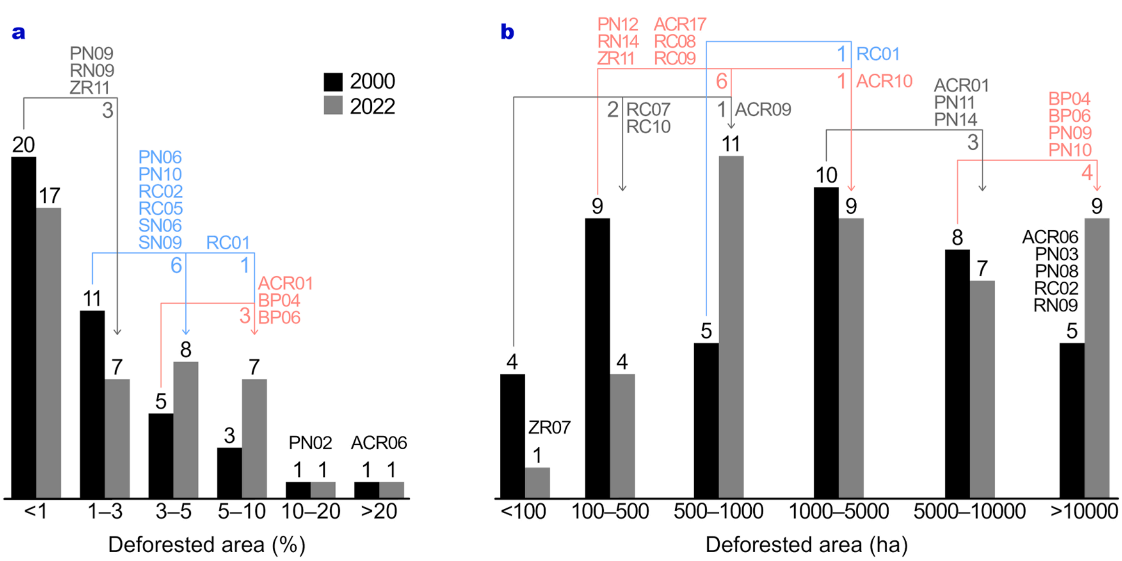

Fig. 4. Frequency of natural protected areas (NPA) according to deforested area (DA).

tended to have higher rates than their respective surrounding areas (Fig. 3).

3.2. Standardized effectiveness index (EI)

Of the 41 NPAs analyzed, 9 NPAs (22 %) were non-effective, 31 NPAs (76 %) were moderately-effective and only one NPA was effective (PN09 'Cordillera Azul National Park', Fig. 3). The total box and whisker (n = 41) show that the average EI was 3.127, 50 % of NPAs obtained EI between 3.042–3.423, the minimum EI was 0.591 from ACR06 and the maximum EI was 4.502 from NP09 (Fig. 5). The indirect-use NPAs (which include PN [IUCN Category II] and SN [IUCN Category III]) presented a slightly higher mean EI than the direct-use NPAs (which include BP, RC, RN [IUCN Category VI] and ACR), with values of 3.304

Table 1
Classification of natural protected areas (NPAs)* according to categories of the percentage of deforested area (DA% 2022) and rate of change (DAr).

DA%	DAr 2000–2022			
	Recovery	Steady	Low	High
Low	–	–	ACR04, ACR09, ACR10, ACR17, **PN03**, **PN08**, **PN09**, **PN10**, **PN11**, **PN12**, **PN13**, **PN14**, RC03, RC05, RC06, RC07, RC08, RC09, RC10, RN08, RN09, RN12, RN14, **SN06**, **SN07**, ZR03, ZR07	ACR01, BP04, BP06, **PN06**, **PN07**, RC01, RC02, RC04, RN10, **SN08**, **SN09**, ZR11
Medium	–	–	–	**PN02**
High	–	–	–	ACR06
Very high	–	–	–	–

* Indirect use of NPAs (strict protection) in bold type.

and 3.002 (difference of 0.302). The difference is reduced when looking at the median (difference of 0.034) or box boundaries.

At the SINANPE category level of NPA, PNs [IUCN Category II] presented the highest average EI (3.414), followed by RN (3.322), RC (3.247), SN [IUCN Category III] (3.001), ACR (2.823), and BP (1.513). The two BPs evaluated (BP04 and BP06, EI≤1.857) were non-effective. ACR06 (EI=0.591, non-effective) influences the low mean of the ACRs that generally had 3<EI<4 (moderately-effective). All SINANPE categories had at least one NPA categorized as non-effective (EI<3). Of the three ZRs evaluated, ZR11 'Nieva River Reserved Zone' (EI=2.820) was categorized as non-effective but its EI is close to the limit of moderately-effective (3<EI<4). This borderline pattern was also observed in PN06 'Abiseo River National Park' (2.966), SN09 'Cordillera de Colán National Sanctuary' (2.923), and RN10 'Allpahuayo Mishana National Reserve' (EI=2.884). In the group of 31 NPAs (76 %) moderately-effective, RN09 (EI=3.911) presented an EI close to effective (EI>4), while RC02 (EI=3.031) and SN07 'Pampa Hermosa National Sanctuary' (EI=3.053) presented EI close to non-effective (EI<3). At the level of IUCN NPA categories, Category II Ecosystem protection and recreation had the highest average EI (3.414), followed by Category VI Sustainable use of natural resources (3.065) and Category III Conservation of unique natural features (3.001).

In general, it was observed that the year of creation ($r = 0.291$, $p = 0.070$) and size ($r = 0.268$, $p = 0.097$) of the NPA showed weak positive correlations with the EI value, but these were not statistically significant. Similarly, the classification (indirect or direct, $t = 1.530$, $p = 0.135$) and administration (national-SERNANP or regional, $t = 0.779$, $p = 0.468$) of the NPA did not show statistically significant differences in the EI value. Therefore, none of these factors demonstrated a significant influence on the EI value and effectiveness categorization (Fig. 6). Four national NPAs, created in 1987 (BP04 and BP06) and 1988 (RC01 and SN08), and one regional NPA (ACR06, 2010) presented the lowest EI (EI≤2.526). The smallest and at the same time oldest NPA presented an EI of 3.327 (PN02), which is higher than the mean (3.127). The largest NPA, decreed in 2004, had an EI of 3.417 (NP11 'Alto Purús National Park').

3.3. Effectiveness index (EI) and SERNANP tools

The change to a standardized approach in the calculation of EI influenced the results, as three parameters were adjusted from a binary to a continuous scale (Figs. 3 and 7a). The standardized EI (mean=3.127, median=3.249, SD=0.659) showed lower values compared to the binary EI (mean=4.559, median=4.782, SD=0.689), while the binary EI also appeared more tightly clustered. Both indices maintained a strong and statistically significant correlation ($r = 0.836$, $p < 0.001$) (Fig. 7d–e). In the binary approach, five of the non-effective NPAs from the standardized approach (PN06, RN10, SN08, SN09 and ZR11) were effective, and 30 of the 31 moderately-effective NPAs were effective (Figs. 3 and 7a).

A very low correlation ($r = 0.141$, $p = 0.418$, $N = 35$, ACR do not have METT) was found between METT (Fig. 7b) and standardized EI, with contrasting cases such as BP06 and ZR03 'Santiago Comaina Reserved Zone' (Fig. 7d). In contrast, CS (Fig. 7b) and standardized EI showed a moderate correlation ($r = 0.462$, $p = 0.002$, $N = 41$), with notable outliers such as ACR06, BP06, and BP04. Similarly, a very low correlation ($r = 0.010$, $p = 0.954$) was observed between METT and binary EI; while CS and binary EI displayed a moderate to strong correlation ($r = 0.586$, $p < 0.001$, $N = 41$) (Fig. 7e).

4. Discussion

4.1. Loss of peruvian Amazonian forest (PAF)

Based on the latest geospatial data from MINAM (2024b), it was found that the deforested area was 7.15 % of the PAF territory in 2000. By 2022, the deforested area increased to 10.88 % of the PAF territory, with a loss of 2.92M ha, which is verifiable in MINAM (2024a). MINAM (2024b) was used because it is the official Peruvian source for PAF monitoring. However, a limitation of this dataset is that it only covers the PAF and not the entire Peruvian territory, where many other NPAs remain unanalyzed in this study. Therefore, future studies could complement this analysis with geospatial data from sources such as Global Forest Watch (www.globalforestwatch.org/), Global Forest Change

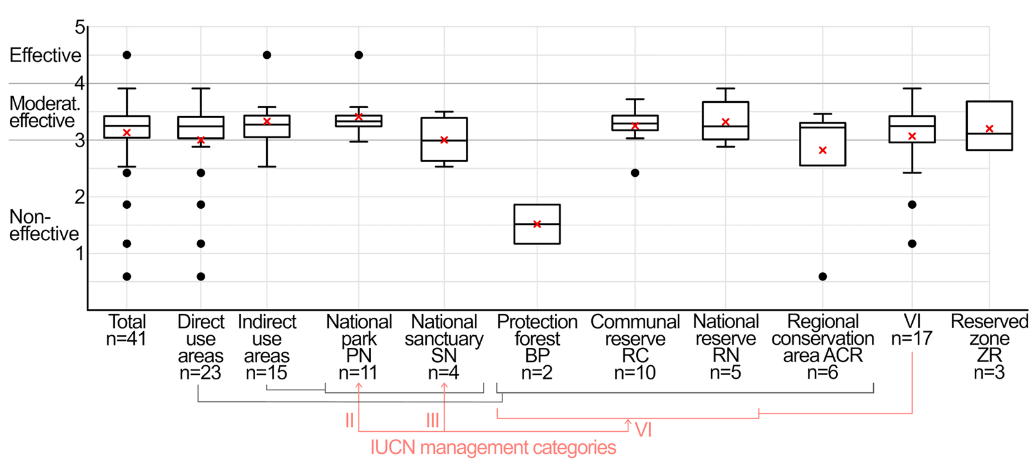

Fig. 5. Effectiveness Index (EI) of natural protected areas (NPAs) grouped according to use classification (direct and indirect) and conservation category.

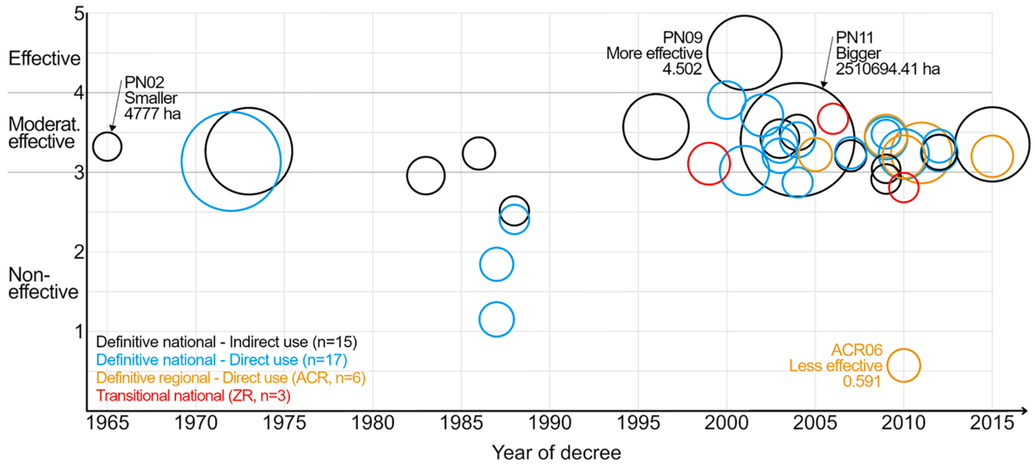

Fig. 6. Distribution of natural protected areas (NPAs) according to their effectiveness index (y-axis), year of decree (x-axis), and surface area (size of circle).

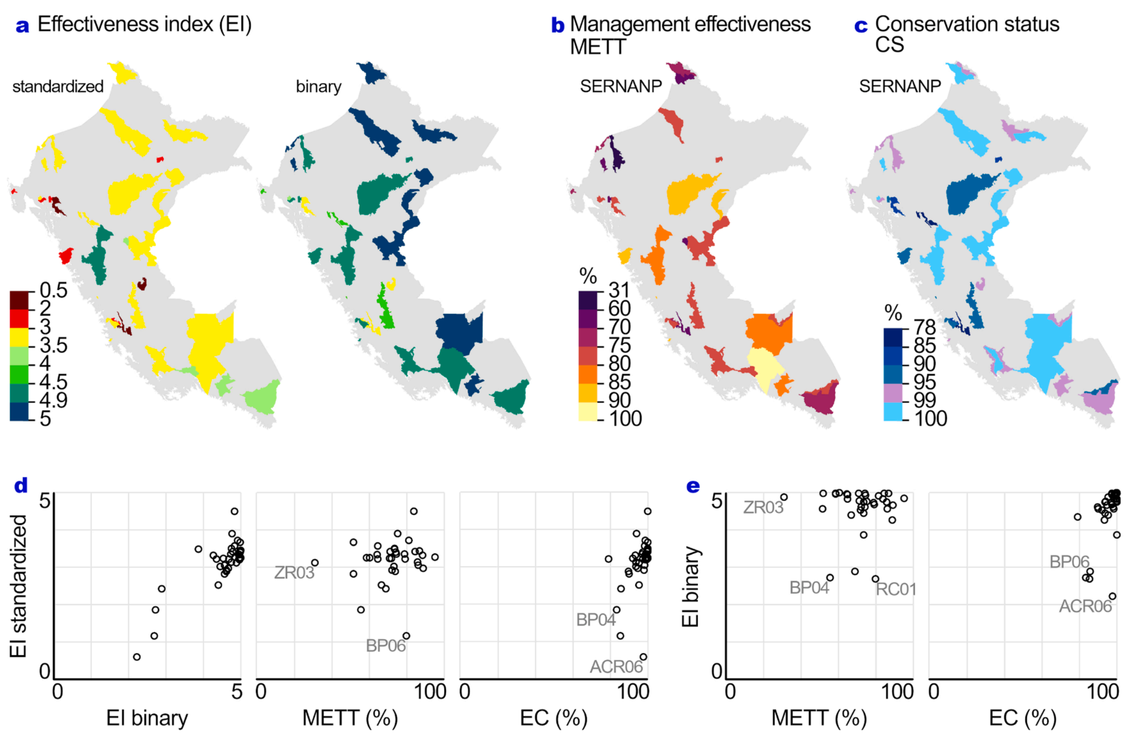

Fig. 7. Standardized and binary effectiveness index (EI) of natural protected areas (NPAs), management effectiveness (METT), and conservation status (CS) of SERNANP, and correspondences for the NPAs evaluated in this study.

(Hansen et al., 2013), or MapBiomas (https://peru.mapbiomas.org/).

To better understand the effectiveness of NPAs in containing deforestation, it is essential to consider the key drivers of Amazonian forests loss, as they directly influence the patterns and dynamics observed in this study. The drivers of Amazonian forests loss have been widely discussed (Cruz et al., 2023; De Sy et al., 2015; Hänggli et al., 2023). One assumption about deforestation in the Peruvian Amazon is that migratory, small-scale, or subsistence agriculture is the main driver, according to government documents (e.g., MINAM, 2015) and specific studies (e.g., Rojas-Briceño et al., 2019). However, this premise is based on remote sensing of the size of deforestation patches, but not on field data, potentially combining different drivers under an overly general umbrella (Ravikumar et al., 2017). Móstiga et al. (2024b) identified 14 potential drivers of deforestation in Peru, related to legal, informal and illegal economic activities, such as agriculture, forestry or mining, favored by road accessibility. They then mapped nine frequent drivers and rates of deforestation at the district level, performing a national trajectory model that explained 34 % of the total observed variance; and showed that temperature, agriculture, transportation network, precipitation, rural population, and fire had a positive effect, while slope harmed deforestation (Móstiga et al., 2024a).

4.2. Effectiveness of NPAs to contain deforestation in Peru

The trend shows that NPAs were moderately effective in containing deforestation. However, there are different scenarios in the LULC change processes of NPAs, which would imply different risks and different mitigation strategies (Figueroa et al., 2011). This is particularly important in NPAs that, although they have low DA%, present high DAr. Greater deforestation was evidenced in surrounding areas than within NPAs; in agreement with previous studies (Cotrina-Sánchez et al., 2021a; Dourojeanni, 2015). Greater deforestation has also been reported in unprotected (not necessarily surrounding) than in protected areas in Peru (Móstiga et al., 2024b) and in the Amazon (Finer and Mamani, 2023).

The average DAr and EI show that, although indirect-use NPAs (which include PN [IUCN Category II] and SN [IUCN Category III]) are slightly more effective than direct-use NPAs in containing deforestation processes, this difference is not statistically significant. This observation aligns with previous statements (Dourojeanni 2014; 2015; 2023). Similarly, the METT (Arenas and Cortez, 2023) and CS (SERNANP, 2024c) tools also identify slight, non-significant differences in the means. Specifically, the observation that indirect-use NPAs (e.g., National Parks) have similar deforestation rates to direct-use NPAs (e.g., Communal Reserves) suggests potential management challenges in strictly protected areas. These issues may stem from resource constraints, enforcement gaps, or external pressures, such as illegal logging or agricultural expansion. However, the medians DAr and EI even out the situation, even reversing it in some NPAs. This aligns with findings from Rico-Straffon et al. (2022), who found that multiple-use NPAs were no worse for forests protection than strict (indirect use) NPAs: each type of NPA blocks deforestation increases in unprotected forests, and even multiple-use NPAs do slightly better.

RC02 presented the highest net loss of PAF, and it has been reported that agricultural activity and illegal gold mining are the main causes (Novoa et al., 2016). In addition, the branching of a forest road was detected entering RC02, which overlaps with a forestry permit obtained after its creation, although timber forest extraction is not permitted (Villa and Finer, 2019). Forest roads have also been detected in the buffer zone of RC04 'Asháninka Communal Reserve' and native communities north of RN08 (Finer et al., 2020). BP06 presented the highest DAr, and remote sensing of forests during 1996–2006 and prediction of risk zones, also reported high deforestation, mainly due to coffee farming and migration from other regions to the Alto Mayo Valley (de Oliveira and Mendoza, 2013). Faced with this, in BP06 they developed a novel pilot forest monitoring system integrating satellite imagery, acoustic sensors, and drones (Wright et al., 2018). In addition, comprehensive strategies for the sustainable tourism use of BP06 have been proposed, considering its plans and planning tools aimed at ecosystem conservation (Nuñez-Torres et al., 2023).

RN09 presented the highest DAr in its surrounding area. Namely, in the southern Peruvian Amazon, gold mining has eliminated PAF in the buffer zone of RN09 (mainly), PN08 'Bahuaja-Sonene National Park', and RC03 'Amarakaeri Communal Reserve' (Finer and Mamani, 2024; Nicolau et al., 2019).

Mennonite settlements deforest directly but also build and maintain roads that facilitate access to ACR06 (NPA with the highest DA%) and to a native community of the Shipibo ethnic group (Dourojeanni, 2022; Sierra, 2021). The expansion of the road network in the last decade in the Peruvian Amazon has increased the rate of deforestation, but the increase in protected areas has partly mitigated this effect (Aguirre et al., 2021). PN02 presented the second-highest DA% but also presented the second-lowest net loss of PAF. Remote sensing of forest cover during 2006–2023 (Puerta and Iannacone, 2023; Zuloaga and Gabriel, 2023) highlights that PN02 has complied with forest conservation due to the actions of SERNANP and the local community, which coincides with the calculated EI. However, the 2006–2023 maps identify extensive areas as forest, which are actually DA (mainly No forest in 2000) from MINAM (2024a, 2024b), and this could be reassessed in future studies.

Overall, NPAs in the Peruvian Amazon are moderately effective in protecting forest. It is stated that their performance in preventing deforestation in protected areas has improved (Dourojeanni, 2023). However, efforts in NPAs must be maintained and increased, as different models predict areas close to NPAs with high deforestation risk in Peru (Cotrina-Sánchez et al., 2021a; Rojas et al., 2021; Vijay et al., 2018) and the Amazon (Flores et al., 2024). This implies that further efforts should be made to improve management (Arenas and Cortez, 2023) and the way to monitor the effectiveness of Peruvian NPAs (WCS, 2020).

4.3. Approach to calculating the effectiveness index (EI)

The EI was previously designed and applied in multiple NPAs in Mexico (Sánchez-Cordero et al. 2007; Figueroa and Sánchez-Cordero 2008; Figueroa et al. 2009; 2011; Aguilar et al., 2020) and also applied in four private-communal NPAs in northern Peru (Delgado et al., 2021). These studies used a combination of binary and standardized parameters, whereas this study proposed using only standardized parameters. The standardized approach is more rigorous, as it does not assign the same score to all NPAs with lower rates than their context but rather evaluates them based on how much better they perform compared to their surroundings. Additionally, it avoids overestimating the effectiveness of NPAs by preventing the disproportionate concentration of high scores. While effectiveness indices are highly useful for providing a general, systematic, and quantitative assessment of NPAs, relying solely on them to evaluate their effectiveness is not advisable (Figueroa et al., 2011). Therefore, it is essential to interpret index values and classifications with caution and to supplement them with a detailed diagnosis of processes specific to each PA.

Future studies should address these issues in the Peruvian context, considering the ecological and socioeconomic diversity of the country. It is necessary to explore how the specific characteristics of each NPA, such as its location, management category, and socioeconomic context, influence its effectiveness (Figueroa and Sánchez-Cordero, 2008). Additionally, it is recommended to analyze the interaction between land-use change processes and local conservation policies, as well as to incorporate broader indicators of ecological integrity, such as ecosystem structure, function, and composition. It would also be valuable to assess how pressure in surrounding areas affects the effectiveness of NPAs and whether this pressure is a consequence of their existence. Finally, future methodologies should prioritize combining quantitative analyses with qualitative diagnostics to better understand underlying dynamics and design adaptive management strategies that respond to the specific risks identified.

4.4. Evaluation of the effectiveness of NPA in Peru

Although one would expect a high correspondence between NPA management and the conservation of their ecosystems, SERNANP determined a very low correlation ($r = 0.1054$, $p = 0.3681$, $N = 76$) between METT and CS (Arenas and Cortez, 2023). This study also found a very low correlation between METT and EI. First, as the METT report is a self-assessment of each NPA, there may be an under- or overestimation. Second, the METT (average 64.60 % in 2022) reflects processes and intermediate management results but does not necessarily translate directly into impact results, such as the CE of the NPAs. Therefore, third, the high CE (average 96 % in 2022) may be due to geographic location, inaccessibility, particularities, or singularities of the territorial matrix that influence the good CE of some NPAs. It is necessary to emphasize that, to mitigate, treat, and reduce threats affecting conservation elements, it is necessary to maintain, strengthen, and improve management conditions in the NPAs of SINANPE (Arenas and Cortez, 2023).

Although the CS and EI showed a moderate correlation. Ecological effectiveness indices, such as the EI of this study, are useful because they provide a general, systematic, and quantitative overview, but should not be the only basis for evaluating effectiveness (Figueroa et al., 2011). Figueroa and Sánchez-Cordero (2008) recognize at least six possible shortcomings of the IE, such as that NPAs tend to be in less disturbed areas, so that current differences may reflect previous conditions and not their effectiveness, or that the maps used, although the best available, are not free of errors that may affect direct comparison. It is important to complement with detailed analyses in each NPA (such as diagnosis of CS effects and activities) and to integrate aspects of design and management effectiveness (Delgado et al., 2021; Lee and Abdullah, 2019). EI is suggested as a complement to SERNANP's CS and METT, considering the characteristics and limitations of each analysis. EI can also be an input to the conceptualization document for monitoring in Peruvian NPAs (WCS, 2020).

4.5. Other approaches

On the one hand, in addition to the relatively simple measurement of forest extension loss, given the constant development of large volumes of remote sensing data and its derived products on a global scale, the new trend in ecology is to measure the integrity of forests. Hansen et al. (2021) propose a framework to use remote sensing data to monitor and evaluate the integrity of the forest ecosystem, which is a measure of the structure, function, and composition of an ecosystem in relation to the range of variation determined by the climatic-geophysical environment. Furthermore, for Colombia, Ecuador, and Peru, indicators of forest quality have been developed with the aim of effectively monitoring and maintaining ecological integrity (Hansen et al., 2024).

On the other hand, in Peru, the distribution of key species (SDM) has been modeled, including *Tremarctos ornatus* (Meza et al., 2020), *Rupicola peruvianus* (Meza et al., 2023), *Xenoglaux loweryi* (Meza et al., 2022), *Tapirus terrestris* (Guzman et al., 2023), *Lagothrix flavicauda* (Guzman et al., 2022), *Cinchona* ssp. (García et al., 2022) and *Cedrela* ssp. (Cotrina-Sánchez et al., 2021b), whose potential maps have been overlaid with the NPAs to understand the potential protected area. Using stacked SDMs can be a strategy to evaluate the design effectiveness of current NPAs; or to design future NPAs in species hotspots (Condro et al., 2021).

5. Conclusions

The effectiveness of 41 NPAs in containing the loss of PAF was evaluated using an index constructed with parameters such as deforested area and its rate of change, both in each NPA and in their geographic contexts. The results shows that NPAs were moderately-effective in containing deforestation, scenarios vary significantly, requiring tailored mitigation strategies. This is particularly relevant for NPAs with a low deforested area (%) but high deforestation rates, highlighting the need for immediate action. This study provides a solid preliminary diagnosis of the effectiveness of NPAs, offering a quantitative and systematic assessment of SINANPE's conservation performance and identifying NPAs needing urgent interventions. The proposed approach is straightforward, replicated, and adaptable, benefiting from the wide availability of remote sensing products. These findings underscore the importance of integrating spatially explicit metrics into conservation strategies, supporting more precise evaluations and enhancing the effectiveness of management by SERNANP in its challenging role of safeguarding biodiversity.

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CRediT authorship contribution statement

Nilton B. Rojas-Briceño: Writing – original draft, Software, Investigation, Data curation, Conceptualization. **Verónica Cajas-Bravo:** Writing – original draft, Investigation. **Alexander Pasquel-Cajas:** Software. **Betty K. Guzman:** Methodology, Conceptualization. **Jhonsy O. Silva-López:** Methodology, Conceptualization. **Jaris Veneros:** Writing – review & editing, Funding acquisition. **Ligia García:** Writing – review & editing, 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.

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Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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