

Research Paper

Integrating agroecological suitability of cacao (*Theobroma cacao* L.) with biodiversity and land-use constraints in Peru

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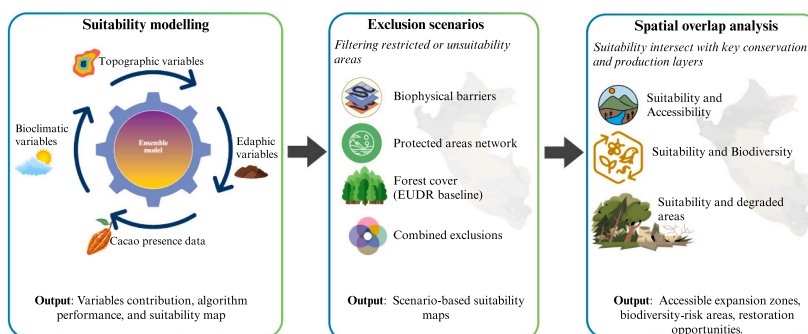
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HIGHLIGHTS

- Ensemble modelling identified cacao suitability across Peru.
- Four exclusion scenarios revealed biodiversity and conservation conflicts.
- High suitability overlaps occurred in Andean-Amazon transition zones.
- Degraded suitable lands highlight opportunities for agroforestry restoration.
- Findings provide spatial inputs for sustainable land-use planning and EUDR.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Cacao cultivation is vital for rural economies in Peru, but its expansion often overlaps with sensitive ecosystems, raising concerns for biodiversity conservation. Despite international commitments to deforestation-free supply chains, integrated analyses combining agroecological suitability with land-use constraints remain scarce in Peru.

OBJECTIVES: This study aims to identify suitable areas for cacao cultivation under multiple exclusion scenarios, evaluate conflicts with biodiversity and conservation areas, and quantify degraded lands that could provide opportunities for agroforestry-based restoration.

METHODS: Cacao suitability was modelled with an ensemble of nine machine-learning algorithms using bioclimatic, edaphic, and topographic predictors. Outputs were filtered to exclude biophysical barriers and

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overlaid with national-scale layers of species richness, protected areas, forest cover, and degraded lands through GIS-based spatial analysis to evaluate exclusion scenarios and trade-offs.

RESULTS AND CONCLUSIONS: The ensemble achieved high predictive power, with Random Forest (AUC = 0.997) and XGBoost (AUC = 0.972) performing best. Highly suitable areas were concentrated in the Andean-Amazon transition, especially in San Martín, Cusco, Huánuco, and Junín departments, where they overlapped with biodiversity hotspots and legally protected areas. Degraded yet suitable lands highlighted opportunities to expand cacao through agroforestry systems, reducing forest pressure and enhancing ecological restoration.

SIGNIFICANCE: By integrating suitability modelling with national-scale geospatial layers, this study delivers a framework linking crop suitability with land-use constraints. The findings support national-scale planning while remaining adaptable to local contexts. They also align with international policy frameworks such as the European Deforestation Regulation (EUDR), promoting sustainable cacao production, biodiversity conservation, and long-term rural development in Peru.

1. Introduction

Cacao (*Theobroma cacao* L.) cultivation has become increasingly important in the Peruvian Amazon, serving as an economic alternative for local communities and as a strategy to replace illicit coca crops (Orozco-Aguilar et al., 2021; Paredes and Pastor, 2024). Over recent decades, regions such as San Martín, Junín, Ucayali, Huánuco, and Cusco have experienced a marked rise in production, with national output increasing more than sixfold between 2000 and 2021 (MINAGRI, 2016; Solidaridad, 2023). By the end of 2024, cacao export revenues were projected to approach 1.3 billion USD (Ninahuanca Abregu, 2025). This growth has been supported by policies such as the National Plan for the Development of the Cacao-Chocolate Value Chain to 2030, aimed at strengthening the production chain, business organization, and multi-sectoral integration to enhance participation in external markets (MIDAGRI, 2020). Nevertheless, despite deforestation-free agriculture commitments, concerns remain over agricultural frontier expansion and primary forest conversion, including for cacao (Finer et al., 2020; Ivanova et al., 2020; Selibas, 2024). Such conversion drives ecosystem fragmentation and biodiversity loss, affecting endemic species and disrupting ecological functions, underscoring the role of cacao-based agroforestry in conserving endangered species (Aycart-Lazo et al., 2025; González et al., 2024).

Beyond current biodiversity threats from forest conversion, climate change is expected to exacerbate risks by altering agroclimatic conditions (Gateau-Rey et al., 2018; Watts et al., 2022). This may push cacao cultivation into new areas, necessitating the use of more resilient genotypes to adapt to the changing climate (Ceccarelli et al., 2021). Such expansion could overlap with high-biodiversity zones, underscoring the need for sustainable practices that maintain or enhance biodiversity and ecosystem services, as observed in African landscapes (Kamath et al., 2024; Sassen et al., 2022). Agroforestry systems have proven beneficial for biodiversity and soil fertility in South America (Allen et al., 2024; Rocha et al., 2019; Suárez et al., 2021). In Peru, they serve as biodiversity reservoirs for insects and significantly influence soil fungal communities (Arévalo-Gardini et al., 2020; Perry et al., 2016). However, spatial analyses remain lacking to pinpoint cacao-suitable areas with low biodiversity risk or potential for agroforestry-based ecological restoration.

Previous studies in Peru have modelled cacao suitability by integrating bioclimatic, topographic, and edaphic variables using approaches such as the Analytic Hierarchy Process (AHP), Maximum Entropy (MaxEnt), and their combination (Rojas-Briceño et al., 2022). Ensemble models have incorporated future climate projections (Ceccarelli et al., 2021), while Random Forest (RF) models have been applied to map cadmium concentrations in soil and cacao beans (Thomas et al., 2023a). Although national-scale mapping, regional assessments (Castro-Nunez et al., 2021), and local data collection reports (Bustamante et al., 2022; Oliva-Cruz et al., 2022), these efforts have not been integrated into an approach linking cacao suitability with biodiversity, protected areas, and landscape patterns. Such integration is essential for land-use strategies that balance agricultural production

with forest protection, aligned with REDD+ and EU deforestation-free regulations (Kamath et al., 2024).

Considering that the EU regulation on deforestation-free products is scheduled to take effect from December 30, 2025 (European Union, 2024), establishing that products like cacao must not come from areas with deforestation occurring after December 31, 2020, there arises an urgent need to align national production systems with sustainability standards (European Parliament, Council of the European Union, 2023). This is especially relevant for Peru, where 2020 registered the highest annual Amazonian forest loss (203,272 ha), and more than 3 million hectares have been lost since 2000, mostly in patches smaller than 5 ha (MINAM, 2025a). Such fragmentation disrupts ecological connectivity, alters habitat structure, and increases the vulnerability of many species. This situation is even more concerning considering that Peru is one of the ten most megadiverse countries globally (MINAM, 2014), making biodiversity loss a critical risk. Given these conditions, areas with the highest agroecological suitability for cacao are expected to spatially coincide with zones of high biodiversity value and protected areas, particularly along the Andean-Amazon transition where optimal climatic and edaphic conditions frequently overlap with ecologically sensitive landscapes. At the same time, degraded lands located within suitable zones may provide opportunities to mitigate these potential trade-offs by enabling cacao expansion through agroforestry systems without adding additional pressure on remaining forests.

In this context, the present study aims to identify potentially suitable areas for cacao cultivation in Peru under four exclusion scenarios; considering biophysical barriers, protected areas, forest cover, and their combinations to evaluate conflicts with protected areas and biodiversity risks, and to quantify degraded lands within suitable zones, providing spatial input for strategic and sustainable land management. Specifically, it seeks to: i) model cacao suitability by integrating climatic, edaphic, and topographic variables to delineate areas with the highest cultivation potential; ii) evaluate biodiversity and conservation risks under the four exclusion scenarios by overlaying suitability outputs with spatial data on species richness, protected areas, and anthropogenic pressures; iii) quantify the extent of degraded and accessible areas within suitable zones for cacao cultivation, to provide spatial input for future planning and land management decisions.

2. Materials and methods

2.1. Study area

The study area covers the Peruvian territory, approximately 1,285,000 km², with the eastern region dominated by the Amazon basin (Fig. 1a), characterized by dense rainforest, high temperatures, and intense rainfall. Peru's complex topography ranges from lowland coastal areas at sea level to Andean peaks exceeding 6700 m a.s.l.s (Fig. 1b). It also hosts a network of Protected Natural Areas (PNAs) under the National System of Natural Areas Protected by the State (SINANPE), classified by level and category (Fig. 1c). PNAs may be national, regional, or private/local. National PNAs include definitive categories National

Parks (NP), Protected Forests (PF), Communal Reserves (CR), National Reserves (NR), National Sanctuaries (NS), Historic Sanctuaries (HS), Landscape Reserves (LR), Wildlife Refuges (WS), and Hunting Grounds (HG), and transitional Reserved Zones (RZ). Regional PNAs correspond to Regional Conservation Areas (RCA), and private/local PNAs correspond to Private Conservation Areas (PCA) (Congreso de la República del Perú, 1997). Among definitive PNAs, indirect-use categories (NP, NS, HS) prohibit resource extraction or environmental modification, while direct-use categories (PB, CR, NR, WS, HG, RCA) allow resource exploitation under management plans (SERNANP, 2021).

2.2. Modelling cacao suitability

2.2.1. Cacao presence data

Cacao presence points depicted in Fig. 1d, were compiled from previous studies at the global scale (Kamath et al., 2024), georeferenced occurrence data from international databases such as the Global Biodiversity Information Facility (GBIF.org, 2025), as well as field observations from national and regional studies (Bustamante et al., 2022; Ceccarelli et al., 2021; Oliva-Cruz et al., 2022). Considering that these records originate from heterogeneous years and sampling efforts, and to reduce spatial and temporal biases associated with accessibility and uneven reporting across production regions, duplicate records with identical coordinates were removed, and spatial filtering was applied to retain a single presence per grid cell, as considered in similar approaches (Ceccarelli et al., 2021; Rojas-Briceño et al., 2022).

2.2.2. Environmental variables

Multiple environmental, ecological, and anthropogenic datasets were used to support modelling and spatial analysis, selected to represent the agroecological requirements that define the conditions for cacao cultivation (Arvelo Sánchez et al., 2017; INIA, 2019). Climatic variables describe the dominant gradients of temperature and moisture that determine where cacao can grow and thus delimit its potential suitability across tropical landscapes (Bunn et al., 2018). These variables were obtained from the WorldClim v2.1 database, which provides ~1 km resolution climate surfaces based on 1970–2000 averages (Fick and Hijmans, 2017). In addition, metrics representing terrain conditions that influence drainage and local microclimates were included, as they capture topographic requirements relevant for delineating the potential distribution of cacao (González-Orozco and Pesca, 2022; Rojas-Briceño

et al., 2022). This topographic information was obtained from the Shuttle Radar Topography Mission (SRTM) digital elevation model at 30-m resolution, provided by the United States Geological Survey (USGS), from which, slope and aspect were derived. To complement these variables, bioclimatic and topographic layers were obtained from the ENVIRONMENTAL Rasters for Ecological Modelling (ENVIREM) dataset (Title and Bemmels, 2018). Soil data considered as key determinants of cacao suitability and long-term sustainability, included due to the strong influence of soil physical and chemical properties on cacao suitability, cadmium dynamics, and production potential (Arévalo-Gardini et al., 2015; Arévalo-Hernández et al., 2019; Scaccabarozzi et al., 2020), were retrieved from SoilGrids v2.0 (ISRIC-World Soil Information) at 250 m resolution (Poggio et al., 2021), including pH (H₂O), organic carbon, sand and clay percentages, bulk density, and depth to bedrock for topsoil and subsoil. All variables (49) were resampled and spatially aligned to 1 km resolution using bilinear interpolation in QGIS 3.40 (QGIS Development Team, 2024), following approaches in (Brun et al., 2020; Smith and Santos, 2020).

Multicollinearity was assessed using the Variance Inflation Factor (VIF) in the “sdm” R package (Naimi and Araújo, 2016), removing variables with VIF > 10 (Naimi et al., 2014). To avoid oversampling, one occurrence point per raster cell was retained (Elith et al., 2020; Fourcade et al., 2014; Lamboley and Fourcade, 2024). The final dataset comprised 15,684 occurrence records (Fig. 1d), corresponds to areas where cacao cultivation is reported, capturing soil and the environmental conditions associated with its occurrence (Ceccarelli et al., 2021; Thomas et al., 2023a). A complete list of variables considered is presented in Table S1 (Supplementary Material), with the 18 selected predictors highlighted in bold following the VIF analysis.

2.2.3. Suitability modelling

To delineate potential cacao cultivation areas, an ensemble modelling approach was implemented using the “biomod2” package (version 4.2–6-2) (Thuiller et al., 2012) in the R software version 4.5.0 (R Core Team, 2025). Biomod2 supports 12 algorithms: artificial neural networks (ANN), generalized additive models (GAM), classification tree analysis (CTA), multivariate adaptive regression splines (MARS), flexible discriminant analysis (FDA), generalized linear models (GLM), generalized boosted models (GBM), random forest (RF), Maximum Entropy (MAXENT.Phillips and MAXNET), surface range envelope (SRE), and eXtreme Gradient Boosting (XGBOOST) (Guéguen et al., 2025).

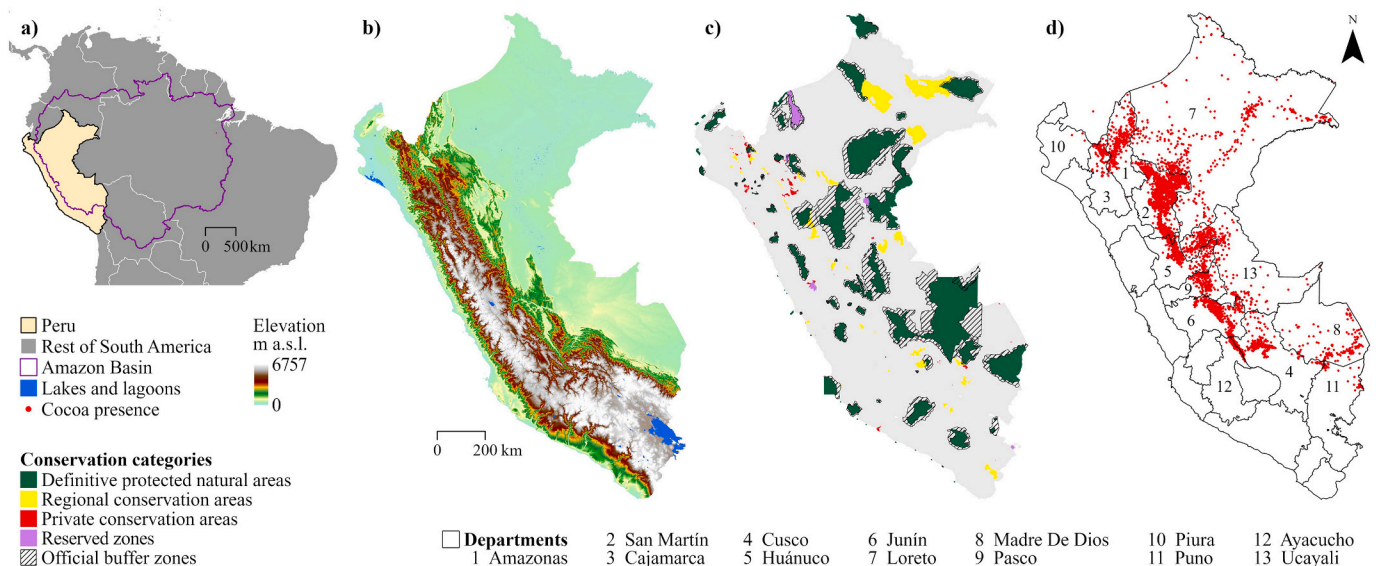


Fig. 1. Study area: (a) Peru within South America; (b) elevation gradient; (c) network of Protected Natural Areas (PNAs) by category; (d) presence records of cacao (*Theobroma cacao* L.).

These models require both balanced present and absence records (Leta et al., 2019; Thuiller et al., 2009), where the response variable represents the presence or absence of cacao cultivation. Presence records correspond to observed locations of cacao production, whereas absence conditions were represented by randomly generated pseudo-absence points with the same number as true-presence cacao records (Huang et al., 2020). Observed cacao presence was used as a proxy for agroecological suitability, assuming that existing cultivation reflects locations where cacao has been viable under current environmental and management conditions. Models were trained with 80% of occurrences and tested with 20% (Hebbar et al., 2024; Leta et al., 2019), each algorithm was run repeated 10 times, and a k-fold cross-validation method to reduce model variance was used (Zhang et al., 2024). Models' performance was assessed using the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC), and true skill statistics (TSS); where AUC values closer to 1.0 indicate excellent performance, while values above 0.8 are considered good in ecological modelling (Swets, 1988), and TSS scores >0.6 are deemed acceptable (Allouche et al., 2006). Individual models with AUC > 0.9 and TSS > 0.7 were selected for the ensemble modelling (Li et al., 2024; Liu et al., 2025). Based on these criteria, SRE, MAXNET and ANN were excluded. In the case of ANN, the algorithm failed to construct a functional neural network during model execution. Therefore, the final ensemble model was built using 90 individual models (9 algorithms × 10 repetitions).

Variable contributions were calculated prior to ensemble construction. The 'build.clamping.mask' option flagged extrapolation zones, and the mean probability across models was used for ensemble prediction (Leta et al., 2019). The ensemble model produced a continuous suitability raster (0–1000), with higher values indicating greater suitability (Hebbar et al., 2024). Values were scaled to 0–1 and reclassified into four categories: unsuitable (0–0.2), low (0.2–0.4), moderate (0.4–0.6), and high (>0.6) suitability (Zhang et al., 2019). This classification aids spatial interpretation and subsequent overlay analyses with biodiversity and physical barriers. For further analysis, only areas with suitability >0.2 (categories 2–4) were considered.

2.3. Available suitable area for cacao production

Biophysical and legal barriers that could limit cacao expansion were integrated following Kamath et al. (2024), resulting in four analytical cases.

Case 1 excludes suitability areas where cacao cultivation is technically unfeasible due to extreme hydrological conditions, permanent water coverage, low temperatures, or the presence of consolidated infrastructures and land uses incompatible with agricultural expansion. This exclusion includes bofedales (high Andean wetland), water bodies, glacier, coastal wetland, island, mangrove, periglacial, river, mining area, and urban areas, based on land cover classes from the Ecosystem Map of Peru (MINAM, 2019), as well as road infrastructure surfaces at national and departmental levels provided by the Peruvian Ministry of Transport and Communication (MTC) (Ministerio de Transportes y Comunicaciones, 2025).

Case 2, adds legal restrictions to Case 1 by excluding areas under formal conservation status, including PNAs and their buffer zones (BZ), RCA, RZ, and PCA, as depicted in the study area (Fig. 1c). Spatial data were obtained from the Servicio Nacional de Áreas Naturales Protegidas por el Estado (SERNANP) (SERNANP, 2025).

Case 3 incorporates forest cover exclusions to Case 1, aligning with the EUDR, which requires cacao to originate from areas without deforestation after 2020. Forest cover data were sourced from the Global Map of Forest Cover 2020 – Version 2 (Bourgoin et al., 2024) by the Joint Research Centre (JRC) of the European Commission.

Case 4 applies all restrictions from the previous cases, representing a fully constrained scenario that integrates biophysical, legal, and deforestation-free criteria.

2.4. Identifying areas suitable and accessible for cacao cultivation

Highly suitable cacao areas located near major cities are likely to expand first, as better market access and lower transport costs promote agricultural growth in the Peruvian Amazon (Aguirre et al., 2018; Cruz et al., 2023). To identify these zones, a spatial overlay was performed combining cacao suitability with accessibility. This last was derived from the global travel time raster by (Weiss et al., 2018), which estimates travel time to the nearest city (>50,000 inhabitants). This layer was reclassified into four quantile-based categories (1–4), with higher values indicating shorter travel times. Bivariate maps were then generated, with one axis representing cacao suitability and the other accessibility within those suitable areas.

2.5. Identification of potential biodiversity risks

Following (Kamath et al., 2024), potential biodiversity risk areas for future cacao expansion were identified by overlaying cacao suitability zones with a Rarity-Weighted Richness (RWR) raster, derived from Area of Habitat (AoH) data for birds and mammals from the IUCN Red List-version 2021–3 (IUCN, 2025). AoH refines species ranges by applying habitat and elevation filters, improving biodiversity distribution resolution. The RWR layer was reclassified into four quantile-based categories and overlaid with cacao suitability to highlight areas of high ecological sensitivity.

Additionally, a single multi-dimensional red-green-blue composite map was produced by combining reclassified rasters of cacao suitability (2–4), accessibility (1–4), and biodiversity value (1–4), enabling visual identification of priority zones where high accessibility and suitability coincide with high biodiversity, indicating potential ecological risk.

2.6. Identification of areas with restoration potential through cacao cultivation

To identify degraded lands suitable for cacao, the suitability map was intersected with the 2022 national degraded land map from (MINAM, 2025). This dataset, previously applied in restoration and land suitability studies (Cotrina Sánchez et al., 2021; Rojas Briceño et al., 2020), classifies degradation into seven types grouped into four categories: undegraded, low (forest fragments), medium (negative Net Primary Productivity – NPP; changes in vegetation cover – CVC; combinations of negative NPP with forest fragments or CVC), and high (forest loss or forest loss combined with negative NPP).

3. Results

3.1. Model performance and variable contributions

The RF model achieved the highest predictive performance among all individual algorithms (AUC:0.997, TSS of 0.935), followed by XGBOOST (AUC: 0.972, TSS: 0.850). In contrast, FDA (AUC: 0.942, TSS: 0.766) and GAM (AUC: 0.950, TSS: 0.775) showed the lowest performance (Fig. 2a). The relative importance of the five most influential environmental variables varied across algorithms (Fig. 2b). PETWettestQuarter was the most important overall (mean: 15.7%, max: 45.3%), particularly for FDA and GLM. Bio03 (Isothermality) followed closely (mean: 15.6%, max: 41.9%), with high importance in CTA and XGBOOST. Bio15 (Precipitation seasonality) averaged 11.3% (max: 32.0%), notably in GAM. Topographic wetness index (topoWet) averaged 9.0% (max: 29.6%), with higher contributions in FDA and GAM, while Bio13 had the lowest importance (mean: 1.7%, max: 4.3%).

3.2. Potential distribution

Excluding biophysical barriers (Case 1; Fig. 3a), San Martín concentrates the largest suitable area for cacao cultivation (33,143.99 km²,

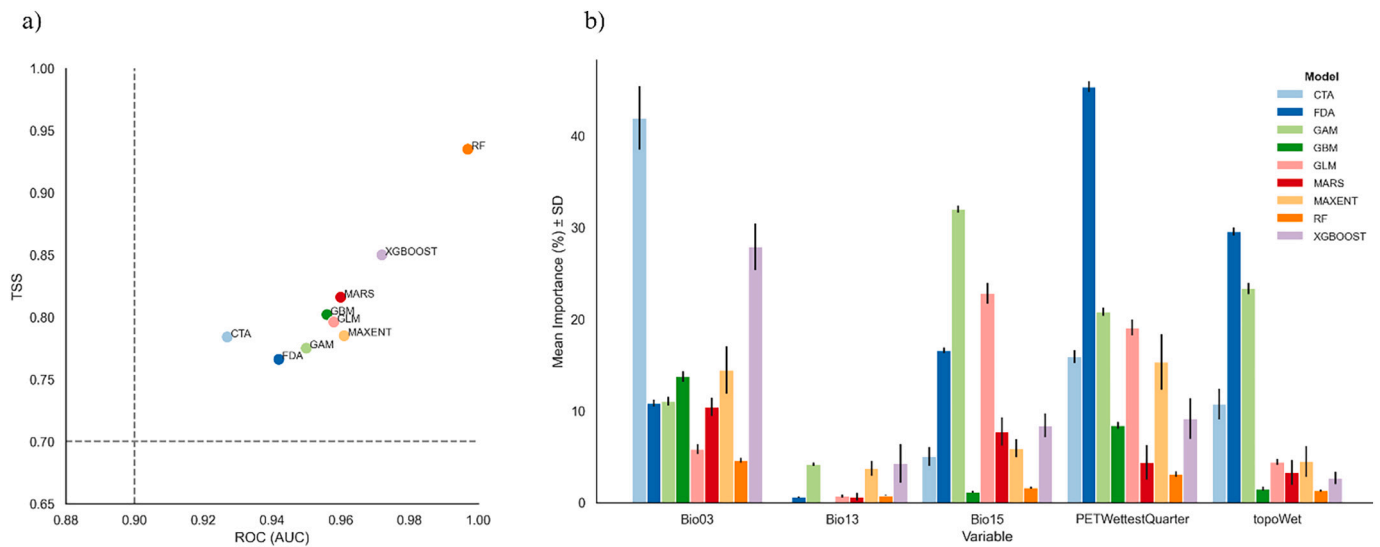


Fig. 2. Performance (AUC and TSS) of individual algorithms used in the ensemble model (a). Mean relative importance of the five most influential environmental predictors across algorithms (b).

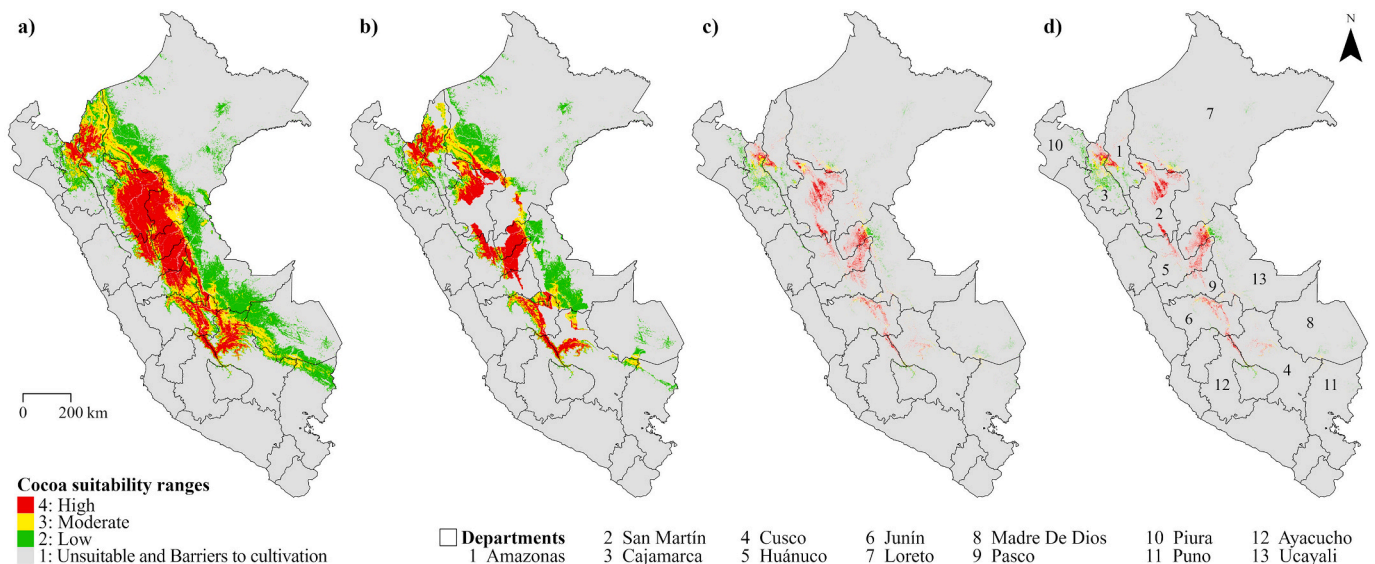


Fig. 3. Spatial distribution of suitable areas for cacao cultivation under four exclusion scenarios: a) Biophysical barriers excluded (Case 1); b) Case 1 plus protected areas (Case 2); c) Case 1 plus forest cover (Case 3); d) Case 1 plus both protected areas and forest cover (Case 4).

65% of its territory), followed by Ucayali (15,038.02 km²; 14.3%), Huánuco (14,175.42 km²; 37.8%), and Cusco (11,032.19 km²; 15.3%). When legally protected areas are also excluded (Case 2; Fig. 3b), San Martín remains dominant (14,626.89 km²; 28.7%), with Huánuco (10,711.88 km²; 28.6%) and Ucayali (9441.55 km²; 9%) also showing substantial areas. Excluding forest cover instead (Case 3; Fig. 3c) reduces available land, yet San Martín (7016.46 km²; 13.8%) and Huánuco (3487.97 km²; 9.3%) continue to lead. Under the most restrictive scenario (Case 4; Fig. 3d), which combines all previous exclusions, San Martín still retains 4618.00 km² (9.1%) of suitable land and Huánuco 2827.23 km² (7.5%).

The overlap between cacao cultivation suitability (Fig. 3a) and the PNAs network with their official buffer zones (BZ) (Fig. 1c) shows that most high-suitability areas are more extensive in BZ (37,489.30 km²) than PNAs themselves (20,530.94 km²) (Fig. 4). BZ of indirect-use PNAs account for a larger share (24,130.01 km²) compared to direct-use PNAs (13,334.94 km²), a pattern also observed inside PNAs (13,501.72 vs. 6697.53 km², respectively). ZR (309.89 km²) and PCA (21.81 km²)

contain only small areas of high cacao suitability. The distribution by PNA shows that Cordillera Azul, Río Abiseo, and El Sira stand out for the largest extents of high suitability, both inside their boundaries and within their buffer zones, often coinciding with areas of high biodiversity.

3.3. Accessibility of area potentially available and suitable for cacao

Areas combining high cacao suitability and high accessibility (value 4 in the bivariate maps) likely correspond to current cultivation areas or priority zones for expansion, with their distribution varying across the four scenarios (Fig. 5). In Case 1 (Fig. 5a), the largest extents were in San Martín (9971.91 km²), Ucayali (3686.19 km²), and Huánuco (3652.66 km²). When excluding protected areas (Case 2, Fig. 5b), these departments retained substantial areas: 6903.30 km², 3585.19 km², and 2998.42 km², respectively. Excluding forest cover (Case 3, Fig. 5c) reduced suitable areas to 4861.54 km² in San Martín, 1835.19 km² in Ucayali, and 1455.51 km² in Huánuco. Applying all exclusions (Case 4,

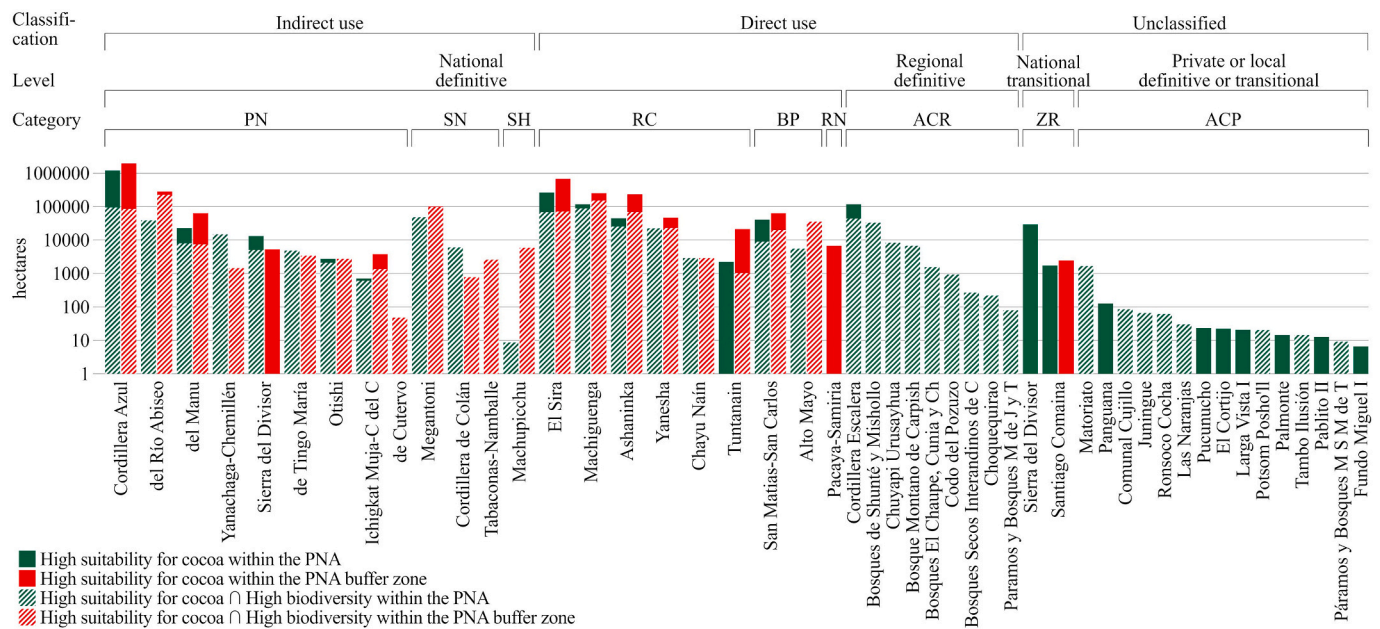


Fig. 4. Area of high cacao suitability and its overlap with high biodiversity within Protected Natural Areas (PNA) and their buffer zones, grouped by use category (indirect, direct, unclassified) and legal status.

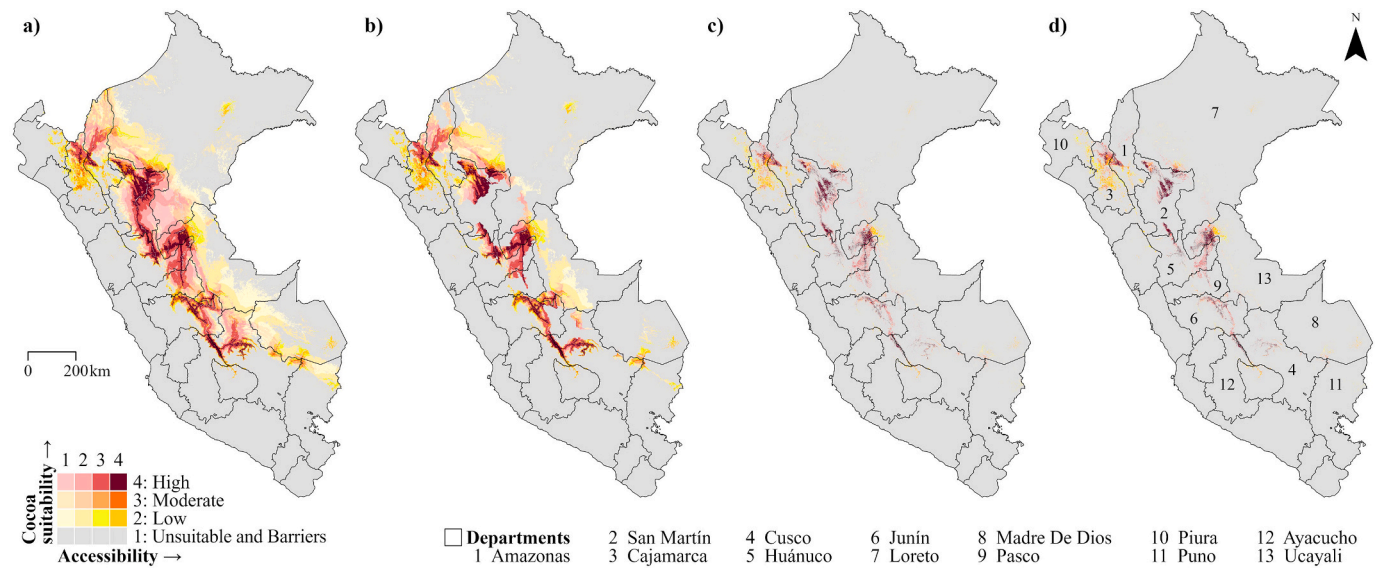


Fig. 5. Spatial distribution of areas combining high cacao suitability and accessibility (value 4 in bivariate maps) under four exclusion scenarios: a) Case 1 – biophysical barriers excluded; b) Case 2 – plus protected areas; c) Case 3 – plus forest cover; d) Case 4 – all exclusions combined. Accessibility is measured as travel time to the nearest major city. Dark red indicates highest accessibility and suitability.

Fig. 5d) left 3675.57 km², 1811.03 km², and 1149.30 km², respectively.

3.4. Areas of potential biodiversity risks

Zones combining high cacao suitability and high biodiversity value (value 4 in bivariate maps) represent potential biodiversity risk, with patterns varying across the four scenarios (Fig. 6a-d). In Case 1, the largest overlaps occurred in San Martín (14,112.62 km²), Cusco (8775.10 km²), and Huánuco (6069.67 km²). In Case 2, these areas decreased but remained significant in San Martín (9867.43 km²), Huánuco (4847.09 km²), and Cusco (4782.42 km²). In Case 3, overlaps further declined, persisting mainly in San Martín (3131.80 km²), Cajamarca (1327.97 km²), and Junín (978.47 km²). Case 4 retained key areas in San Martín (2831.47 km²), Cajamarca (1325.46 km²), and

Junín (953.10 km²).

The overlap between high suitability and high biodiversity (Fig. 7a) and the PNAs with BZ shows greater extent in BZ (8087.01 km²) than within PNAs (5356.40 km²), in accordance with what is shown in Fig. 4.

Some of the areas at highest potential risk from cacao expansion are those where high suitability, high accessibility, and high biodiversity value overlap. These critical zones appear in the RGB composite maps in Figs. 7a-d, where darker tones, particularly dark green, dark blue, and black, indicate high values in all three dimensions. The largest high-risk areas (value 4 in bivariate maps) were found in San Martín, ranging from 5017.05 km² in Case 1 to 2271.56 km² in Case 4, followed by Cusco (up to 2179.94 km² in Case 1), Huánuco (1894.27 km² in Case 1), and Junín (1740.23 km² in Case 2).

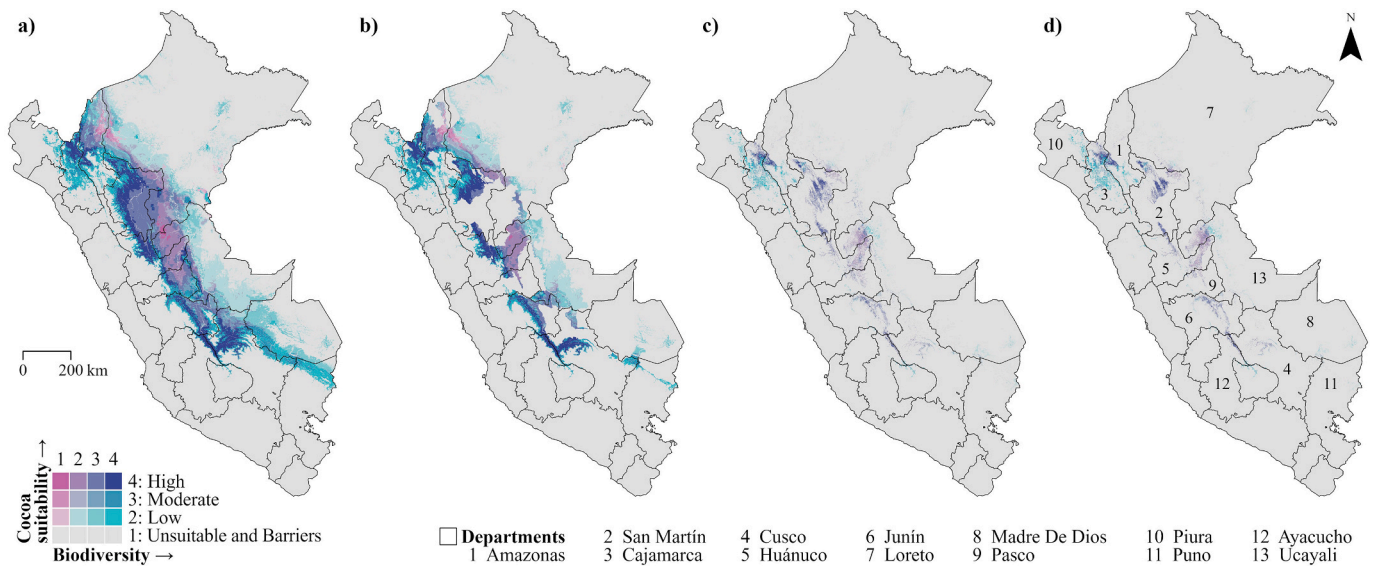


Fig. 6. Spatial distribution of areas combining high biodiversity value and cacao suitability under four exclusion scenarios: a) Case 1 – biophysical barriers excluded; b) Case 2 – plus protected areas; c) Case 3 – plus forest cover; d) Case 4 – all exclusions combined. Dark blue indicates zones with high rarity-weighted species richness and high cacao suitability.

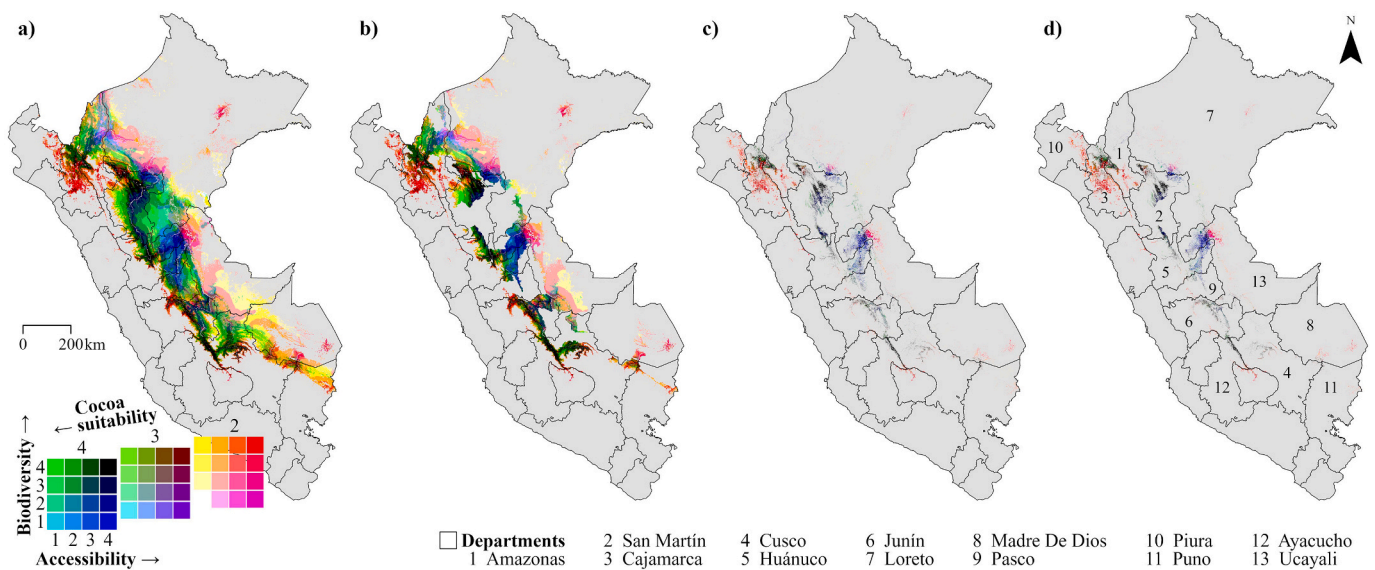


Fig. 7. Spatial overlap of accessibility, biodiversity value, and cacao suitability under four exclusion scenarios: a) Case 1 – biophysical barriers excluded; b) Case 2 – plus PNAs; c) Case 3 – plus forest cover; d) Case 4 – all exclusions combined. Black areas represent the highest values across all three dimensions; white areas represent the lowest.

3.5. Areas with restoration potential through cacao cultivation

Across all scenarios, areas suitable for cacao cultivation on degraded lands, indicating potential for ecological restoration were identified (Figs. 8a-d). In Case 1, the largest areas were in San Martín (4187.66 km²), Huánuco (3592.12 km²), and Ucayali (3010.19 km²), followed by Junín and Pasco. In Case 2, Huánuco (3064.07 km²), Ucayali (2588.48 km²), and San Martín (1942.40 km²) remained dominant. In Case 3, although the total area decreased, Huánuco (1794.56 km²), San Martín (1732.93 km²), and Ucayali (1368.33 km²) continued to be relevant. In the most restrictive Case 4, priority areas persisted in Huánuco (1537.12 km²), Ucayali (1243.86 km²), and San Martín (831.67 km²).

4. Discussion

This study applied an ensemble modelling approach to map cacao cultivation suitability across Peru, integrating environmental, ecological, and anthropogenic dimensions across four geospatial scenarios. This multicriteria framework strengthens spatial planning by identifying areas where agricultural expansion, conservation priorities, and restoration opportunities converge, offering a replicable decision-support tool for different territorial scales.

4.1. Model performance and key predictors

The ensemble modelling approach used in this study highlights the strong influence of climatic, edaphic, and topographic gradients on cacao suitability across Peru. Among the nine machine-learning

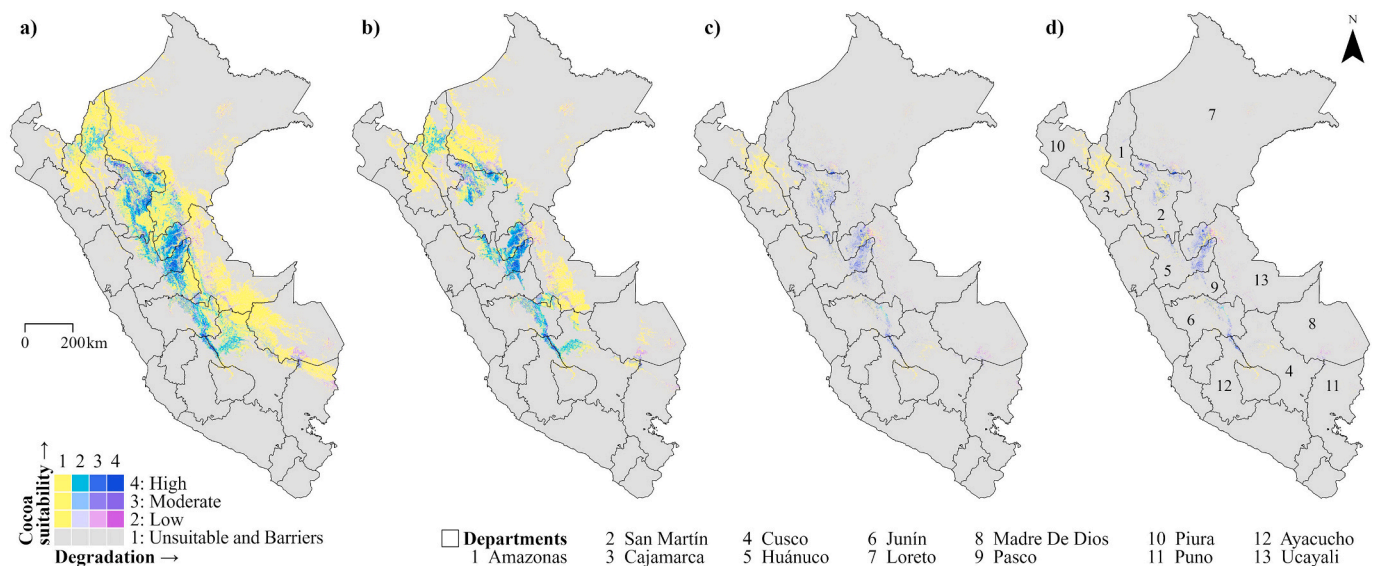


Fig. 8. Spatial distribution of degraded areas with potential for ecological restoration through cacao cultivation under four exclusion scenarios: a) Case 1 – biophysical barriers excluded; b) Case 2 – plus protected areas; c) Case 3 – plus forest cover; d) Case 4 – all exclusions combined.

algorithms evaluated, RF achieved the highest predictive performance (AUC = 0.997; TSS = 0.935), confirming its strong predictive capacity in ecological modelling, both individually and within ensemble approaches (Hebbar et al., 2024; Hounsou-Dindin et al., 2023; Valavi et al., 2021), even its capacity to handle complex interactions and limited samples in undersampled areas (Luan et al., 2020; Mi et al., 2017). XGBOOST also performed strongly, suggesting its potential relevance for future suitability applications, despite its limited use in earlier cacao modelling efforts such as Ceccarelli et al. (2021). MaxEnt, although widely used in SDM (Lisovsky and Dudov, 2021), did not outperform RF or XGBOOST; however, when combined with multicriteria methods (AHP) have successfully mapped cacao suitability in Peru (Rojas-Briceño et al., 2022). In addition, model reliability also depends on the environmental representativeness of the occurrence data. Although the dataset used includes 15,684 records, its value lies in covering the principal climatic and elevational gradients where cacao is grown, even if some regions remain less sampled. Recent efforts to georeferenced cacao parcels under the national EUDR platform are expected to expand occurrence data and strengthen model robustness (MIDAGRI, 2025).

The importance of PETWettestQuarter, isothermality (Bio03), and precipitation seasonality (Bio15) reinforces cacao's sensitivity to water balance and climatic seasonality, consistent with evidence on drought stress, waterlogging, and seasonal rainfall critically influencing yield and flood sensitivity in tropical ecosystems (Ceccarelli et al., 2021; De Almeida et al., 2016; Zuidema et al., 2005). Similarly, the relevance of topoWet reflects the influence of drainage, moisture retention and drainage, and terrain-driven microclimatic variation in Andean–Amazon landscapes (Arévalo-Gardini et al., 2015; INIA, 2019; Sánchez et al., 2017). Although the WorldClim 1970–2000 variables may not fully capture recent climatic shifts (Fick and Hijmans, 2017), this limitation was partially mitigated by incorporating ENVIREM variables (Title and Bemmels, 2018), which provide additional ecophysiological relevant descriptors not included in WorldClim, and help reduce uncertainty in suitability estimation.

4.2. Socio-ecological drivers of spatial patterns

The spatial patterns identified illustrate how favourable agroecological conditions intersect with accessibility, historically shaping cacao expansion in Peru. Regions with favourable agroecological conditions and short travel times are likely to experience the earliest and most

intense expansion, particularly as ageing plantations face declining yields associated with pests, and management constraints (Solidaridad, 2023). Areas with both high accessibility and high cacao suitability particularly in San Martín, Ucayali, and Huánuco correspond to long-established smallholder production frontiers. These patterns align with the evidence that road development, market integration, and demographic have accelerated forest conversion and crop expansion in the Peruvian Amazon (Marquardt et al., 2019; MINAM, 2025a; Suárez de Freitas, 2017). Road networks remain one of the main prediction of forest loss in Peru (Cruz et al., 2023; Lucich et al., 2015), and even fluvially accessible areas, such as parts of Loreto, have experienced forest loss linked to cacao expansion, with 2380 ha converted between 2013 and 2015 (Finer et al., 2020).

While rural populations exert limited local impact on forest loss (Bax et al., 2016), broader demographic dynamics combined soil conditions and rainfall patterns significantly influence regional forest loss trajectories (Bax and Francesconi, 2018; Móstiga et al., 2024). Overall, these findings help contextualise why accessibility amplifies production potential: suitable areas are not only environmentally favourable but also embedded in socio-economic systems that facilitate agricultural expansion. Nonetheless, suitability hotspots in Amazonas and Cajamarca remain underdeveloped, indicating that land tenure, governance, and local incentives may also play decisive roles in determining where cacao effectively expands.

4.3. Conservation conflicts and biodiversity risks

The overlap between high suitability and biodiversity-rich areas, particularly in San Martín, Cusco, Huánuco, and Junín, reflects the ecological configuration of the Andean–Amazon transition, where climatic stability, steep elevational gradients, and structurally complex forests support elevated species richness and favourable agroecological conditions for cacao. This regions also represent the centre of Peru's cacao production (INEI, 2022; Solidaridad, 2023), increasing the likelihood that agricultural expansion will converge with ecologically sensitive landscapes. This convergence occurs within one of the world's principal biodiversity hotspots, where many hotspots remain unprotected in this Andean–Amazon transition zone (Asner et al., 2017; Swenson et al., 2012). The alignment between environmental conditions conducive to cacao cultivation and those that sustain high biodiversity thus explains the recurrent spatial overlap between production potential

and conservation priority areas.

Protected areas and their buffer zones are central to this dynamic. Several Peruvian PNAs are linked to cacao production (MINAM, 2018), and the present analysis identifies Cordillera Azul National Park and its BZ among the most suitable territories. Experiences from Río Abiseo National Park in San Martín, illustrate how agroforestry-based cacao systems can integrate production with conservation goals when effectively governed (Romo, 2018). However, the identified overlap also reveals areas where expansion could exacerbate habitat fragmentation, elevate conservation conflicts, and increase regulatory exposure under emerging zero-deforestation policies. These risks highlight the need to reconcile agricultural development with biodiversity protection through improved monitoring, sustainable intensification, and landscape-based governance approaches.

4.4. Opportunities for restoration and sustainable supply chains

Identifying degraded areas suitable for cacao cultivation offers strategic opportunities to promote cacao expansion without increasing pressure on remaining forests. Agroforestry-based cacao production can support ecological restoration by enhancing soil fertility, which helps restore ecosystem services and support sustainable livelihoods (Asare, 2006; Saputra et al., 2020). These insights are specially relevant in major producing departments where agroforestry interventions can reduce pressure on forests and foster sustainable cacao production (Solidaridad, 2023; Tinoco-Jaramillo et al., 2024).

This restorative potential gains particular importance under the EUDR. The termination of long-standing development programmes such as the United States Agency for International Development (USAID) program that supported smallholder cacao producers for over a decade raises concerns regarding reconversion to illicit crops and renewed forest loss, threatening Peru's deforestation-free cacao exports under the EUDR (Lazo, 2025; Pérez, 2025). Directing expansion toward suitable degraded areas offers a practical pathway to reduce deforestation risk, facilitate traceability, and enhance regulatory compliance within cacao supply chains (Mockshell et al., 2025). Aligning this process with national strategies, including the Plan Nacional para el Desarrollo de la Cadena de Valor de Cacao-Chocolate al 2030 (MIDAGRI, 2020), can help strengthen both ecological integrity and rural development, including the safeguarding of Peru's cacao genetic diversity (Borda et al., 2021; Thomas et al., 2023b).

4.5. Study limitations

To further enhance the robustness and practical relevance of this study, future work could complement the modelling framework. Accordingly, the suitable areas identified in this study are derived from the current spatial distribution of cacao cultivation, reflecting locations where cacao has been established under prevailing environmental conditions. However, the presence of cacao does not necessarily imply optimal productivity or environmentally sustainable management; in some cases, cultivation may occur under suboptimal or degraded conditions. Although the ensemble approach improves predictive robustness, the reliance on presence data for cultivated cacao and pseudo-absences may affect model outputs, requiring independent field validations of cacao presence, helping to reduce the spatial and temporal variability inherent to presence records derived from heterogeneous years and sampling intensities. Although the 1 km spatial resolution of environmental predictors used here are appropriate for national assessments, may overlook fine-scale dynamics relevant to farm-level decisions-making. Therefore, enhancing the precision of land-degradation and biodiversity indicators would likewise increase confidence in the delineation of priority areas.

Moreover, socio-economic drivers such as land tenure, market access, infrastructure quality, and policy incentives would provide a more comprehensive understanding of the drivers shaping cacao expansion

across Peru. Despite these considerations, the integrated patterns identified in this study offer a solid basis for anticipating where suitability, biodiversity pressures, and restoration opportunities converge. Future analyses incorporating finer-scale data and socio-economic variables would further enhance the operational relevance of this framework for guiding sustainable and deforestation-free cacao development.

5. Conclusions

This study demonstrates that integrating climatic, edaphic, and topographic variables through an ensemble modelling framework can reliably predict cacao cultivation suitability across diverse Peruvian landscapes. Integrating these outputs with layers on accessibility, biodiversity richness, and protected areas network, priority regions reveals that suitability regions frequently coincide with conservation priority zones, particularly along the Andean-Amazon transition. These patterns reflect the convergence of favourable agroecological conditions with areas of high ecological value, underscoring the need to manage cacao expansion in ways that avoid reinforcing pressures on vulnerable ecosystems.

The identification of degraded areas within suitable zones highlights meaningful opportunities to promote cacao-based agroforestry systems as a pathway for ecological restoration and climate-resilient production. These insights are highly relevant for emerging deforestation-free regulations such as the EUDR, where directing expansion toward non-forest lands can reduce compliance risks and enhance supply-chain traceability. Taken together, the results provide spatial information to guide land-use planning, strengthen policy decisions, and production with long-term rural development and biodiversity conservation goals in Peru.

CRedit authorship contribution statement

Alexander Cotrina-Sanchez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Betty K. Guzman:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Elgar Barboza:** Writing – review & editing, Investigation. **Manuel Oliva:** Supervision, Project administration. **Angel Fernando Huaman-Pilco:** Writing – review & editing, Project administration. **Nilton B. Rojas-Briceño:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis.

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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

The data and codes that support the findings of this study are available at: <https://figshare.com/s/221b925fe28a972d5854>.

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