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Research

Diverse values regarding nature are related to stable forests: the case of Indigenous lands in Panama

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ABSTRACT. Local land use emerges from peoples' worldviews and values regarding nature. In neotropical forest landscapes, largely inhabited by Indigenous peoples, exploring how Indigenous land use and underlying values may converge with global values such as carbon sequestration and biodiversity conservation may provide lessons to achieve equitable ecological and social outcomes. However, most studies have focused on exploring the influence of Indigenous land use on avoiding deforestation, while few examine how local values relate to deforestation, disturbances, and forest cover stability. To address these gaps, we analyzed deforestation and disturbance spatial-temporal patterns in Indigenous lands in Panama between 2000 and 2020, using a continuous change detection algorithm and generalized additive models. Additionally, we performed participatory mapping across three Indigenous lands to identify instrumental and relational values linked to land use. Our results show that disturbances followed by recovery are the dominant cause of land cover changes in Indigenous lands. Moreover, the area of stable forest cover in Indigenous lands until 2020 was two times higher than in protected areas and other lands lacking protection. The generalized additive models demonstrate that deforestation and disturbance in Indigenous lands exhibit a low density, spatial concentration on forest edges, and temporal stability, explaining forest cover stability. According to participatory mapping, obtaining food from agriculture mainly occurs where deforestation and disturbance are more concentrated. In contrast, other instrumental (i.e., gathering food and household materials) and relational values (e.g., sacred sites) are more dispersed in forests. By weaving scales and perspectives, our results illustrate that diverse values regarding nature framed by Indigenous worldviews can beget stability to forest cover, contributing to Indigenous peoples' quality of life, climate change mitigation, and biodiversity conservation. To align these contributions with global climate and biodiversity targets, it is crucial to disarticulate land ownership from deforestation, grant formal titles to Indigenous lands, and foster equitable incentives to Indigenous peoples.

Key Words: *deforestation; forest cover stability; forest disturbance; Indigenous peoples; instrumental values; land use; Nature's contributions to people; participatory mapping; relational values*

INTRODUCTION

Land use decisions emerge from stakeholders' worldviews and values regarding nature (Ellis et al. 2019). For instance, Indigenous peoples' worldviews encompass beliefs, customary institutions, and knowledge that integrate diverse values in land use practices (Gadgil et al. 1993, Berkes et al. 1995, Berkes 2008). This pluralistic valuation does not privilege livelihoods over nature but reflects a reciprocal relation (Salmon 2000, Walsh 2010, Villalba 2013, Comberti et al. 2015, González and Kröger 2020). Instead, governments and private actors across the globe have usually promoted an economic worldview focused on unidirectional benefits between nature and people, usually privileging one value over others. This unidirectional and unidimensional valuation has resulted in formal institutions and policies that title deforested lands dedicated to food production (Angelsen 2010, Walker 2021), provide results-based payments for carbon sequestration (Sills et al. 2014), or establish protected areas to conserve biodiversity (Börner et al. 2020). Expectedly, stakeholders' contrasting worldviews and values on nature represent trade-offs and even create power imbalances (Pascual et al. 2017, Ellis et al. 2019). In neotropical forest landscapes, largely inhabited by Indigenous peoples (Thiede and Gray 2020), exploring how Indigenous land use and underlying values may converge with global values such as carbon sequestration and biodiversity conservation may provide lessons to achieve effective and equitable ecological and social outcomes.

Numerous studies have analyzed the influence of Indigenous land use on tropical forest landscapes. Previous work has demonstrated that Indigenous land use leads to lower extents of land cover change, deforestation, and fires than private land use (Nepstad et al. 2006, Hayes and Murtinho 2008). Several studies have also controlled the influence of socioeconomic and environmental predictors to establish that Indigenous land use effectively reduces deforestation (Nelson et al. 2001, Nelson and Chomitz 2011, Nolte et al. 2013, Vergara-Asenjo and Potvin 2014, Blackman et al. 2017, Bonilla-Mejía and Higuera-Mendieta 2019, Baragwanath and Bayi 2020, Walker 2021), forests disturbances (Sze et al. 2022), and conserves carbon stocks (Blackman and Veit 2018, Alejo et al. 2021). Other studies have explored whether Indigenous land use can result in stable forest cover and long-term ecological outcomes. According to experts (van Vliet et al. 2013) and household surveys (Gray et al. 2008), Indigenous lands may display large agropastoral footprints and shortened fallows, questioning their capacity to maintain stable forest covers. More recently, studies capturing land use over time and using household surveys (Gray and Bilsborrow 2020), remote sensing (Paneque-Gálvez et al. 2013, Puc-Alcocer et al. 2019, Kunz et al. 2022), or both methodologies (Coomes et al. 2022), suggest that Indigenous land-use and forest cover can remain relatively stable for decades. This land use stability (or instability), and consequently, forest cover stability, depend on various socioeconomic predictors, such as the accessibility to markets (Gray et al. 2008, van Vliet et al.

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2013, Gray and Bilsborrow 2020, Coomes et al. 2022), population density (Herlihy 1985, 1986), and environmental predictors, including forest endowments and topography (Coomes et al. 2016, Sharma et al. 2016). Although forest disturbances (i.e., temporal change in forest cover followed by regeneration) account for ~70% of land use emissions in the tropics (Baccini et al. 2017), these studies have mostly focused on linear interactions between deforestation (forest to non-forest), or a proxy (e.g., cultivated area), and some predictors. Hence, less attention has been paid to non-linear interactions that may quantify where both deforestation and disturbance are concentrated. These interactions could exhibit where forest cover remains stable, indicating how Indigenous land use potentially converges (or diverges) with global forest values.

However, a general perspective of Indigenous land use impacts on forest cover dynamics does not consider context-specific perspectives of values regarding nature. This limitation could explain the shift in research and policy discussion from the ecosystem services (ES) framework to the nature contributions to people (NCP) framework. The former has an economic worldview focusing on unidirectional services to satisfy human ends or instrumental values, and the latter aims to recognize other worldviews and values (Díaz et al. 2018). Originating from bridging government, academic disciplines, Indigenous peoples, and other perspectives, the NCP framework integrates relational values (i.e., values deriving from people-nature relationships) and intrinsic values (i.e., inherent values on nature) regarding nature, highlighting the pervasive influence of culture, and recognizing reciprocal relations between people and nature (Hill et al. 2021). Consequently, the NCP framework represents a boundary concept that bridges diverse stakeholders' worldviews and values, enabling the integration of general and context-specific perspectives to understand people and nature interactions.

A growing body of literature concurs with this boundary concept and has examined instrumental and relational values regarding nature from a context-specific perspective. For instance, Costa-Pierce (1987) described Hawaii's traditional *ahuapua'a* as an integrated land use management system extending from uplands with a sacred and, thus, relational value to more instrumental zones in the midlands and coastal areas for farming and aquaculture. This perspective has been enriched by participatory mapping. Herlihy (1985, 1986) identified the displacement of subsistence zones (i.e., instrumental values) from riverbanks into the forests across Indigenous villages in eastern Panama. More recently, García-Nieto et al. (2019) and Ramirez-Gomez et al. (2016), incorporating spatial models, identified hotspots and overlaps of instrumental values and relational values in rural communities in Spain and Indigenous communities in Guyana, respectively. Further, some studies have analyzed the spatial patterns of values according to environmental predictors. Alessa et al. (2008) established in Alaska that local instrumental and relational values coincide with areas of high biological productivity. Read et al. (2010) showed that hunting in Indigenous lands from Guyana is influenced by the distance to forest edges and slopes and does not usually overlap with relational values. These studies reveal distinctive spatial patterns of instrumental and relational values regarding nature; however, little is known about how Indigenous values relate to land use and forest cover stability and, therefore, to global values linked to climate change and biodiversity.

To address the previous gaps, we explored the spatial patterns of land use changes and values regarding nature in Indigenous lands in Panama (Central America). We argue that Indigenous worldviews are reflected in instrumental and relational values, some of which display spatial patterns related to land use. Considering this spatial interplay between land use and values on nature, our study has two aims: (1) we used remote sensing between 2000 and 2020 at the national scale to estimate the influence of environmental and socioeconomic predictors on deforestation and forest disturbances in Indigenous lands; and, (2) we performed participatory mapping at the local scale among three Indigenous lands (eight communities) in eastern Panama to analyze the influence of environmental and socioeconomic predictors on instrumental and relational values directly related to land use. We show that the distinction between deforestation and forest disturbances reveals land use patterns that facilitate forest cover stability. The participatory mapping in Indigenous lands provides a boundary object for Indigenous and nonindigenous stakeholders to understand which context-specific instrumental and relational values potentially motivate land use change and forest cover stability at the national scale. Overall, our study interweaves a general perspective from remote sensing and spatial modeling with a context-specific perspective of Indigenous values to elucidate equitable pathways toward climate and biodiversity targets.

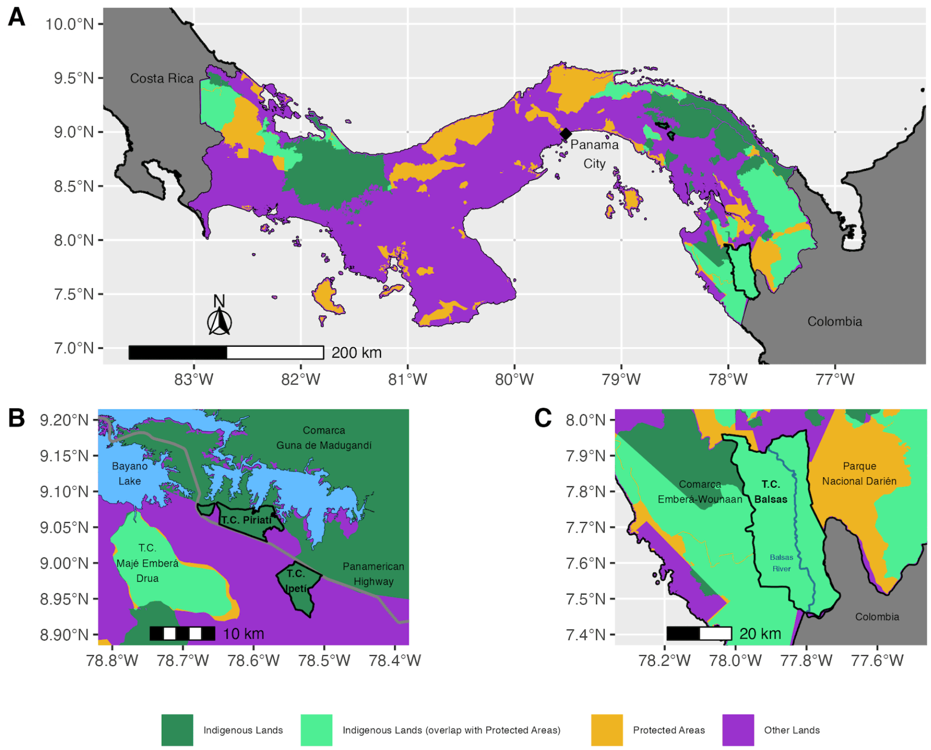
METHODS

Study area

Our national scale analysis was undertaken in Panama, a country that in 2000 maintained 76% of its land cover as undisturbed forest but then lost approximately 3.5% in the past two decades (Hansen et al. 2013). This land cover is mainly tropical moist forest in the country's northern strip and east, along with some remnants of tropical dry forests in the southwest (Olson et al. 2001). In this context, we estimated the area of forest that changed or remained stable in Indigenous lands, protected areas, and public/private lands lacking protected status (other lands; Fig. 1A). Then, we examined the temporal and spatial patterns of deforestation and disturbance in Indigenous lands, the focus of our study. Indigenous lands are home to eight Indigenous groups (Velásquez Runk 2012) and represent a mosaic of land tenure regimes. *Comarcas* may have the status of province (i.e., state or department) or *corregimiento* (i.e., subnational political division), while other Indigenous lands are usually defined as *tierras colectivas* (i.e., collective lands). Some groups within tierras colectivas have obtained legal land titles, and others remain under customary management without formal titling. Regardless of their legal status, Indigenous lands often overlap with protected areas and currently cover ~41% of Panama's area (Vergara-Asenjo and Potvin 2014).

In addition to the national scale analysis, we explored how, at the local scale, instrumental and relational values regarding forests related to the spatial patterns of deforestation and disturbance. To this end, we focused on three Emberá Peoples' Indigenous lands with varying land use histories and levels of market access (Figs. 1B and 1C). Piriatí and Ipetí are located in the Bayano watershed (Panama Province), along the Pan-American Highway, ~100 km from Panama City. These two lands were settled during the 1970s after the government relocated inhabitants living along the Bayano River due to hydroelectric

Fig. 1. Study area. A. National scale of the study: Panama's Indigenous lands, protected areas, and other lands. B. Local scale of the study: Indigenous lands (*tierras colectivas*) of Piriatí and Ipetí (Bayano watershed, Province of Pánama). C. Local scale of the study: Indigenous land (tierras colectivas) of Balsas (Balsas watershed, Province of Darién).



dam construction and related flooding, and they were granted collective titles between 2014 and 2015 after an international legal case (Sharma et al. 2016). Swidden agriculture is a common practice supporting the local livelihoods of Piriatí and Ipetí. Some inhabitants also practice small-scale cattle ranching, rent their lands for mechanized agriculture to *campesinos* (mixed heritage peasants; Sharma et al. 2015) and have salaried jobs outside their communities (Shinbrot et al. 2022).

Further to the east, the third Indigenous land, Balsas, is located in the Darién Province, up to the Panama-Colombia border, and is not connected to the national road network. This Indigenous land along the Balsas River watershed encompasses six communities only accessible by dugout canoe. The Balsas Indigenous land lacks legal land titles and overlaps with two protected areas: Parque Nacional Darién and Corredor Biológico Serranía Bagre. Compared to Ipetí and Piriatí, salaried jobs are scarce in Balsas, and people's livelihoods largely depend on swidden agriculture, hunting, fishing, and the extraction of timber and non-timber forest products. These varying backgrounds among Indigenous lands could distinguish common land use patterns and values from context-dependent differences.

Geospatial data and processing

Our national and local scale datasets comprised geospatial information on deforestation, disturbance, land tenure, and environmental and socioeconomic predictors (Table 1, Fig. 2). Deforestation and disturbance were estimated using CODED (continuous degradation detection, version 1; Bullock et al. 2020a). This Google Earth Engine (GEE) algorithm relies on Landsat imagery to calculate the normalized degradation fraction index (NDFI) on pixels' time series (Bullock et al. 2020b). Based on the NDFI time series, CODED implements a regression-based algorithm to detect deforestation (forest to non-forest) and disturbance (temporal change in forest cover followed by regeneration) events (Bullock et al. 2020c, Reygadas et al. 2021). These steps result in a land-cover map classifying deforestation, disturbance, stable forest, and stable non-forest. Continuous degradation detection also provides the date of deforestation and disturbance events. We used Hansen et al. (2013)'s data to create a forest mask and delineate the detection of deforestation and disturbance in the period 2000–2020, relying on all surface reflectance Landsat images available throughout this two-decade period. Additionally, we used CODED's land cover and deforestation-disturbance date outputs to estimate deforestation and disturbance in four five-year periods (i.e., 2001–2005, 2006–2010, 2011–2015, and 2016–2020).

Based on CODED's land cover map, we performed an accuracy assessment and area estimation of deforestation, disturbance, stable forest, and stable non-forest, following Olofsson et al. (2014) guidelines. Specifically, we used the AREA2 toolbox in GEE (Arévalo et al. 2020) to create a stratified sample of observations (~3000 pixels) and to visualize time series of satellite images, NDFI, and other spectral indices. This visualization, along with the use of high-resolution reference data from January-April 2021 (Planet Team 2021) allowed us to determine if an

Table 1. Geospatial variables included in the study.

Variable category	Spatial variables	Time period	Original resolution	Source
Land tenure and random effects	Indigenous lands, protected areas, and other lands	2000–2020	NA	Vergara-Asenjo and Potvin (2014) and UNEP-WCMC and IUCN (2021)
Environmental predictors	Slope (deg.)	NA	90 m	CGIAR-SRTM V4 (Reuter et al. 2007, Jarvis et al. 2008)
	Distance to rivers (km)	2022	250 m	STRI (2022) and own calculations
	Distance to forest edge	2000	250 m	Hansen et al. (2013) and own calculations
Socioeconomic predictors	Population density - UN adjusted (people/km²)	2000, 2005, 2010, 2015	1 km	Worldpop and CIESIN - Columbia University (2020)
	Travel time to the nearest city of 50,000 or more people (min.)	2000	920 m	Nelson (2008)
	Road distance (km)	2010	250 m	CIESIN - Columbia University and ITOS - University of Georgia (2013) and own calculations.
Offset	Forest cover	2000	30 m	Hansen et al. (2013)
Outcome variables	Deforestation and disturbance	2001–2020	30 m	Landsat, CODED algorithm in Google Earth Engine (Bullock et al. 2020a)
	Instrumental and relational values in Indigenous lands	2021	NA	Participatory mapping

observation actually corresponded to the land-cover category detected by CODED. We used the plugin AcATAMA in QGIS to assess these observations (Llano 2022). Instead of pixel counting, the resulting error matrix and a stratified estimator were used to calculate the confidence intervals for an accuracy assessment (Appendix 1) and the land cover area categories (Olofsson et al. 2014, Arévalo et al. 2020).

The area estimation of land cover was performed in Indigenous lands, protected areas, and other lands using data curated by the Neotropical Ecology Laboratory (McGill University, Smithsonian Tropical Research Institute) and the World Database on Protected Areas (UNEP-WCMC and IUCN 2021). This geospatial information allowed us to delineate the boundaries of comarcas and tierras colectivas (with and without formal titles), defined here as Indigenous lands. The portions of protected areas not currently overlapping with Indigenous lands were defined as protected areas. Other private and public areas without the status of Indigenous land or protected area were defined as other lands. To understand the temporal and spatial patterns of land cover change in Indigenous lands, the focus of our study, we calculated the density of deforested and disturbed pixels per squared kilometer. A deforested or disturbed pixel is referred to as a "plot." We used plots/km² to have a density measure comparable to the value points obtained through participatory mapping. Deforestation and disturbance densities were outcome variables at the national and local scales.

Additionally, we included multiple environmental and socioeconomic predictors of deforestation and disturbance in our dataset. Slope (Reuter et al. 2007, Jarvis et al. 2008), distance to rivers (STRI 2022), and forest edges were included as environmental predictors. The distance from rivers was calculated from STRI's geospatial data (2022) and the function "distance" in Google Earth Engine (GEE). The distance to forest edges was estimated by delineating forested areas based on the forest cover in 2000 (Hansen et al. 2013) and using the function "get_patches" from the R package landscapemetrics (Hesselbarth et al. 2021). The forest edge is a point of reference to determine the depth of deforestation and disturbance within forested areas or patches.

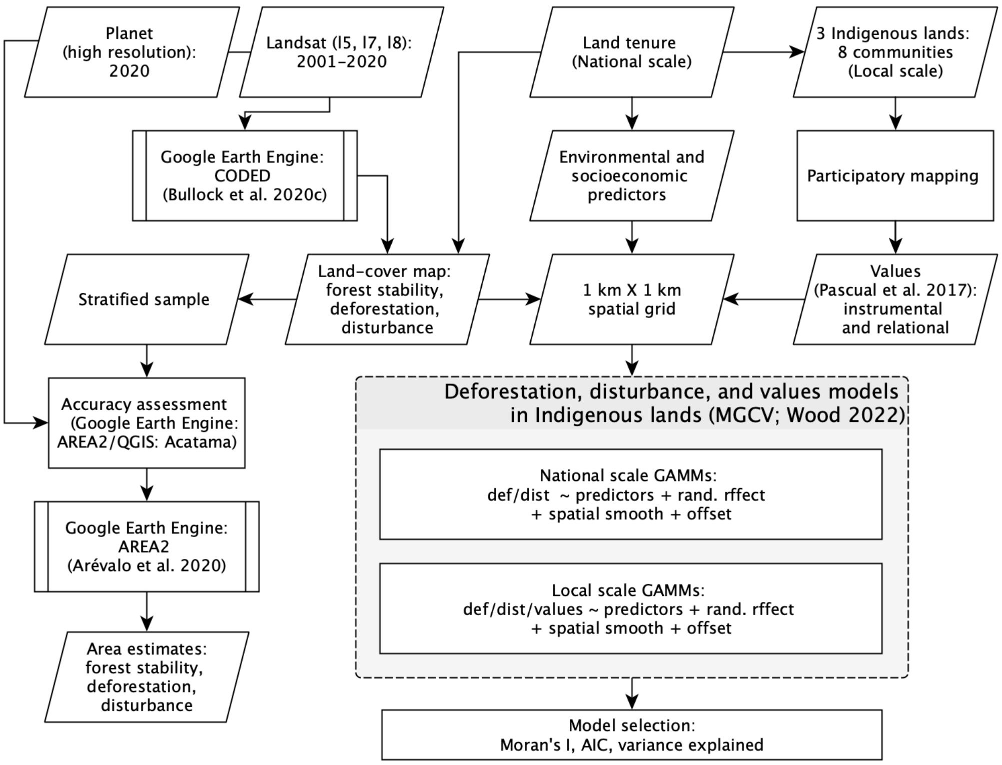
Population density (WorldPop and CIESIN 2020), travel time to city (Nelson 2008), and road distance (CIESIN and ITOS 2013) were used as socioeconomic predictors. Finally, we compensated for the varied spatial resolutions by resampling and extracting all the geospatial information to a country-wide grid database of 1 km resolution (1 km X 1 km cells). Except for the distance to rivers and forest edge, the geoprocessing of tenure, environmental and socioeconomic predictors were performed with the R packages sf (Pebesma et al. 2021a) and stars (Pebesma et al. 2021b).

Participatory mapping

To carry out our study at the local scale, we first received approval from the highest level of Emberá Indigenous authorities in each region, namely the "Congreso General del Alto Bayano" (High Bayano General Congress) in Ipetí and Piriatí, and the "Congreso Regional de Balsa" (Balsa Regional Congress) in Balsas. Additionally, we obtained approval from community-level meetings with *Caciques* and *Nokos*, who are the local Indigenous leaders in these three Indigenous lands. The research activities at this local scale have an ethical certificate for research involving human participants from McGill University Research Ethics Board (File Number:21-03-023).

We performed participatory mapping at the local scale to identify instrumental and relational values regarding forests related to land use. Our study conceived these values as principles and preferences, given a cultural context, which acknowledge humans' interdependence with nature and its contributions to a good quality of life (Pascual et al. 2017). Following the Nature's Contribution to People framework (Pascual et al. 2017, Díaz et al. 2018, Hill et al. 2021), we focused on instrumental values as ones that satisfy human ends and preferences (e.g., regulation of climate, food, and energy materials) and relational values that derive from human-nature relationships (e.g., ways of life, social and cultural identity). Participatory mapping of these values was performed in eight Emberá villages: Ipetí and Piriatí in the Bayano watershed, and Pueblo Nuevo, Galilea, Manené, Bella Vista, and Buenos Aires in the Balsas Indigenous lands along the Balsas watershed.

Fig. 2. A flowchart representing the methodology of our study. The study's national scale generalized additive mixed models (GAMMs) include all Indigenous lands from Panama. The local scale focuses on three Indigenous lands and includes GAMMs on values regarding nature. The random effects were Indigenous land at the national and local scales. The spatial smooth functions account for spatial autocorrelation.



Participatory mapping sessions consisted of focus groups with men and women (3–8 participants) chosen by Indigenous leaders from each community and were developed by at least one Emberá (M.O. in Balsas) and one external facilitator (C.A. in Piriatí, Ipetí, and Balsas). Using medium-extent maps of ~80–100 km² referencing villages, roads (for Piriatí and Ipetí), and surrounding rivers and streams, participants were asked to point out locations valued by their community for providing food from agriculture, food from gathering (e.g., fruits, honey, game, fish), and other materials for households' subsistence (e.g., fibers, firewood, and wood for home construction). After mapping these instrumental values, participants were asked to point to relational values; that is, values associated with the Emberá's way of life, identity, spirituality, and future, such as sacred sites, sacred species, and areas to be maintained for future generations. Given the large geographic extent of Balsas Indigenous lands, we complemented the medium extent participatory mapping with large-extent maps of ~250 km² to locate values distant from the communities. During mapping, the focus group participants explained different aspects of the values, such as species, management practices, traditions, and beliefs. Using QGIS, the resulting maps and values points were digitized and georeferenced. The mapped values were divided into three categories: (1) food from agriculture; (2) food gathering and household materials; and (3) relational. We presume that the first category is related to deforestation and disturbance, whereas the second may only correspond to disturbance. Considering that we focused on values regarding forests, values' points located in non-forest lands in 2000 were excluded from further analysis. Finally, the national database was spatially filtered to the local scale and used to estimate the density per squared kilometer of instrumental and relational values in these three Indigenous lands. The density of instrumental and relational values were outcome variables on the local scale, resulting in a scale and units comparable to deforestation and disturbance.

Spatial patterns of deforestation, disturbance, and forest values

Based on the spatial data, we tested generalized additive mixed models (GAMMs; Wood 2017) to infer the spatial patterns of deforestation, disturbance, and forest values' densities (Appendix 2). At the national scale, the models' outcome variables were deforestation and disturbance density (plots/km²) in the period 2000–2020 and five-year sub-periods (2001–2005, 2006–2010, 2011–2015, and 2016–2020). At the local scale, the models' outcome variables were deforestation and disturbance density during 2000–2020 (plots/km²) along with forest values densities (points/km²). The models included non-linear interactions between the outcome variables and the environmental and socioeconomic predictors. In this case, the smooth functions between predictors and outcome variables were set to a maximum of 10 knots (points joining different smooth functions). The models also included a random effect to account for the variation among Indigenous lands at the national scale and at the local scale (i.e., Piriatí, Ipetí, Balsas). Furthermore, the spatial smooth functions were added to directly account for spatial autocorrelation in the residuals (Keil and Chase 2019). The spatial smooth functions aimed to predict non-linear relations between grid cells' longitude and latitude on the outcome variables. These spatial smoothers were set to 10 knots at the national scale and included tenure as a factor. At the local scale, spatial smoothers were set to five knots, resulting in levels of spatial autocorrelation similar to the national scale. We tested three spatial smooth functions: spheric splines, Duchon splines, and a gaussian process with an exponential correlation (Wood 2017). After model-checking of residuals with different family distributions (e.g., Gaussian, Poisson, Quasi-Poisson, Gamma), we opted for a Tweedie distribution (parameter p ~ 1.5) for all models with a log-link function and the log of forest density in 2000 (forest plots/km²) as an offset term.

For each outcome variable (i.e., deforestation, disturbance, food from agriculture, food gathering and household materials, and relational values) and scale of analysis (i.e., national and local), we selected one final type of model with a specific spatial smooth function based on the lowest AIC and Moran's I statistic, and the highest deviance explained (Appendix 3). When one type of model did not follow those best criteria, we selected the model that was at least best for one criterion and second best for a second and a third criterion. According to this selection, the best models corresponded to a gaussian process with exponential distribution. All models were fitted with the function "bam" in the R package mgcv (Wood 2022) and visualized with mgcViz (Fasiolo et al. 2022). Spatial autocorrelation was assessed with the package spdep (Bivand 2022) using the functions "nb2listw" (creates a weighted list of neighbors) and "moran.test." The selection resulted in two final models at the national scale and five final models at the local scale. To compare models at the national and local scales, we then estimated the relative importance of each explanatory variable (i.e., environmental and socioeconomic predictors, random effect, and spatial smooth) by calculating the change in deviance between a final model and one excluding a given variable while maintaining the others (le Roux et al. 2013).

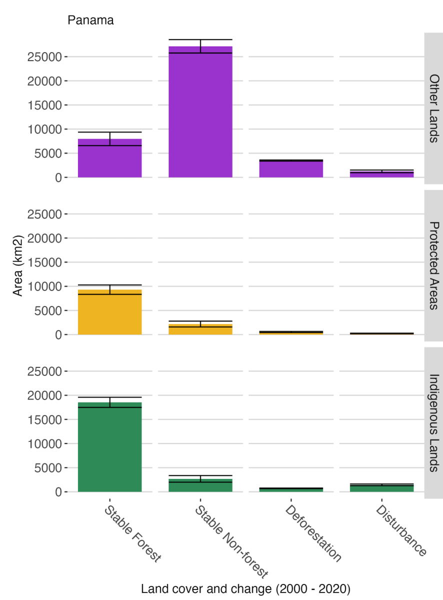
Finally, we tested the differences among the local scale Indigenous lands, that is, Piriatí, Ipetí, and Balsas. First, we used a linear discriminant analysis (LDA) in the R package vegan (Oksanen et al. 2022) to determine to what extent different variables could explain differences between groups (Borcard et al. 2018), in this case, the three Indigenous lands. Specifically, we determined how the outcome variables (i.e., deforestation, disturbance, food from agriculture, food gathering and household materials, and relational values) and socioeconomic and environmental predictors explained differences between Piriatí, Ipetí, and Balsas. After the LDA, we performed in vegan canonical correspondence analyses (CCA) to examine the relationships between the outcome variables and socioeconomic and environmental predictors. The CCA is a weighted redundancy analysis (RDA), which consists of a multivariate multiple linear regression followed by a principal component analysis (PCA; Borcard et al. 2018). Based on LDA results, the CCA was carried out independently in the Bayano (Ipetí and Piriatí Indigenous lands) and Balsas watersheds (Balsas Indigenous lands).

RESULTS

National deforestation and disturbance patterns

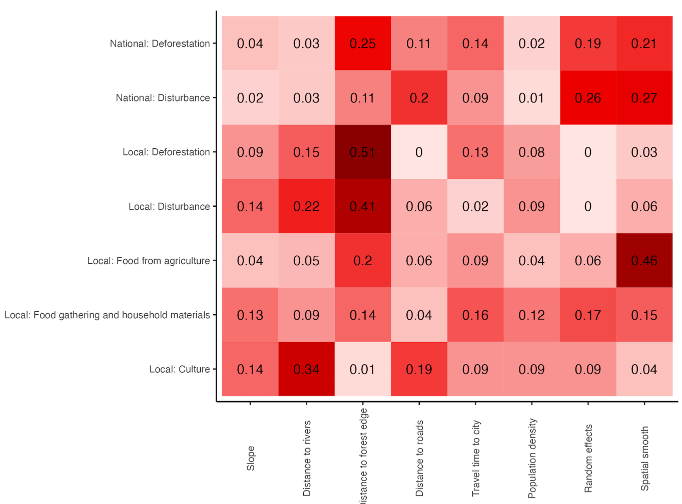
We estimated land cover areas between 2000 and 2020 across different land tenure regimes, including Indigenous lands, in Panama. The landcover change detection algorithm, CODED, had an overall accuracy of ~91% (Appendix 1) and allowed us to estimate the land area that was deforested (forest to non-forest), disturbed (temporal change in forest cover followed by regeneration), or remained as either stable forest or stable non-forest (Fig. 3). Between 2000 and 2020, the area deforested was almost five times higher in other lands lacking protection than in Indigenous lands., i.e., 3482.77 km² (± 113.92 km² 95% CI) in the former and 711.58 km² (± 62.56 km²) in the latter. The deforested area was the lowest in protected areas (540.68 ± 121.98 km²). Forest disturbances occurred in 1238.36 km² (± 269.26 km²), 1444.34 km² (± 180.83 km²), and 222.52 km² (± 65.96 km²) in other lands, Indigenous lands, and protected areas, respectively. Moreover, the area of stable forests until 2020 in Indigenous lands (18537.74 ± 1052.32 km²) was around two times higher than in other lands (7973.77 ± 1398.68 km²) and protected areas (9310.47 ± 972.49 km²). Thus, relative to forests before 2000, 27.43% were deforested, and 9.75% were disturbed in other lands. Regarding protected areas, 5.36% were deforested and 2.2% were disturbed. The same comparison in Indigenous lands implies that 3.33% of forests were deforested, while 6.98% were disturbed. These results suggest that between 2000 and 2020, deforestation was the dominant cause of land cover change in other lands and protected areas. Instead, forest disturbance was the leading cause in Indigenous lands, where most of the forest cover remained stable.

Fig. 3. Land cover change and stability in Indigenous lands, protected areas, and other lands from Panama during the period 2000–2020. Deforestation refers to the conversion of forest to non-forest land cover. Disturbance is a process that does not lead to a permanent change in forest cover and is followed by regeneration. Stable non-forest corresponds to bare land, non-forest vegetation, or areas that were deforested before 2000. The error bars represent confidence intervals based on an accuracy assessment of land cover categories.



Given the limited area of land cover changes and the wide extent of stable forest cover in Indigenous lands, we analyzed the spatial patterns of deforestation and disturbance densities. The models included non-linear interactions with environmental and socioeconomic predictors, a spatial smooth function to control for spatial autocorrelation, and random effects accounting for the variability among Indigenous lands. The best model for both outcome variables contained a spatial smooth function with a gaussian process and exponential correlation structure (Appendix 3). The models had an explained deviance of 55.08% in deforestation density (AIC = 117678.03, Moran's I = 0.007 $p < 0.0001$) and 58.02% in disturbance density (AIC = 97375.50, Moran's I = 0.001 $p < 0.0001$). All variables included in the deforestation and disturbance models were significant ($p < 0.0001$; Fig. 4; Appendix 4). Most of the models' deviance was explained by the spatial smooth (21–27%) and the random effects (19–26%, respectively). The distance to forest edge (25–11%), distance to roads (11–20%), and travel time to city (14–9%) followed in explained deviance for the deforestation and disturbance models. Slope, distance to rivers, and population density explained 4% or less of the deforestation and disturbance deviance at the national scale (Appendix 5). The importance of the spatial smooth function and random effects in the models highlights that local scale dynamics play a key role in land cover change and, thus, deserve further exploration. Still, specific environmental and socioeconomic predictors do explain the spatial patterns of deforestation and disturbance on the national scale.

Fig. 4. Variable importance for generalized additive mixed models (GAMMs) predicting the spatial patterns of deforestation, disturbance, and values regarding nature in Indigenous lands at the national (i.e., Panama) and local scale (i.e., Indigenous lands of Piriatí, Ipetí, and Balsas in eastern Panama).



Despite the moderate influence of roads and travel time to cities on deforestation and disturbance, these predictors reveal patterns at the national scale (Fig. 5). Both deforestation and disturbance in Indigenous lands were particularly dense between 0 and 250 min. (~4 hours) of traveling to cities (up to 4.6 plots/km²). Additionally, deforestation and disturbance densities displayed a slight increase in the least accessible areas to cities (> 1400 min. of traveling). Deforestation and disturbance were below 2.5 plots/km² in the proximity of roads and up to 75 km and had an overall trend to increase in the least road-accessible areas (> 75 km). Disturbance was especially dense (~26 plots/km²) at 85 km from roads. We found that deforestation and disturbance in Indigenous lands for the past 20 years had moderate densities in the proximity to cities and were heavily concentrated in rural areas with limited road accessibility.

The effect of the distance to forest edge was similar for both land cover changes in Indigenous lands at the national scale. At forest edges, deforestation density was ~7 plots/km² and dropped below 1 plot/km² at approximately 2 km inside forest patches. Disturbance was less dense at forest edges (~3 plots/km²) but seemed to occur at slightly higher densities than deforestation more than 2 km inside forest patches. When considering five-year subperiods between 2001–2020, deforestation and disturbance densities had some variation at forest edges (6–17 and 4–6 plots/km²; Appendix 6). Nevertheless, the overall spatial patterns for both land cover changes in forest patches were stable through time. Hence, Indigenous land use exhibits a low density, spatial concentration on forest edges and temporal stability, explaining their relatively stable forest cover for the past 20 years.

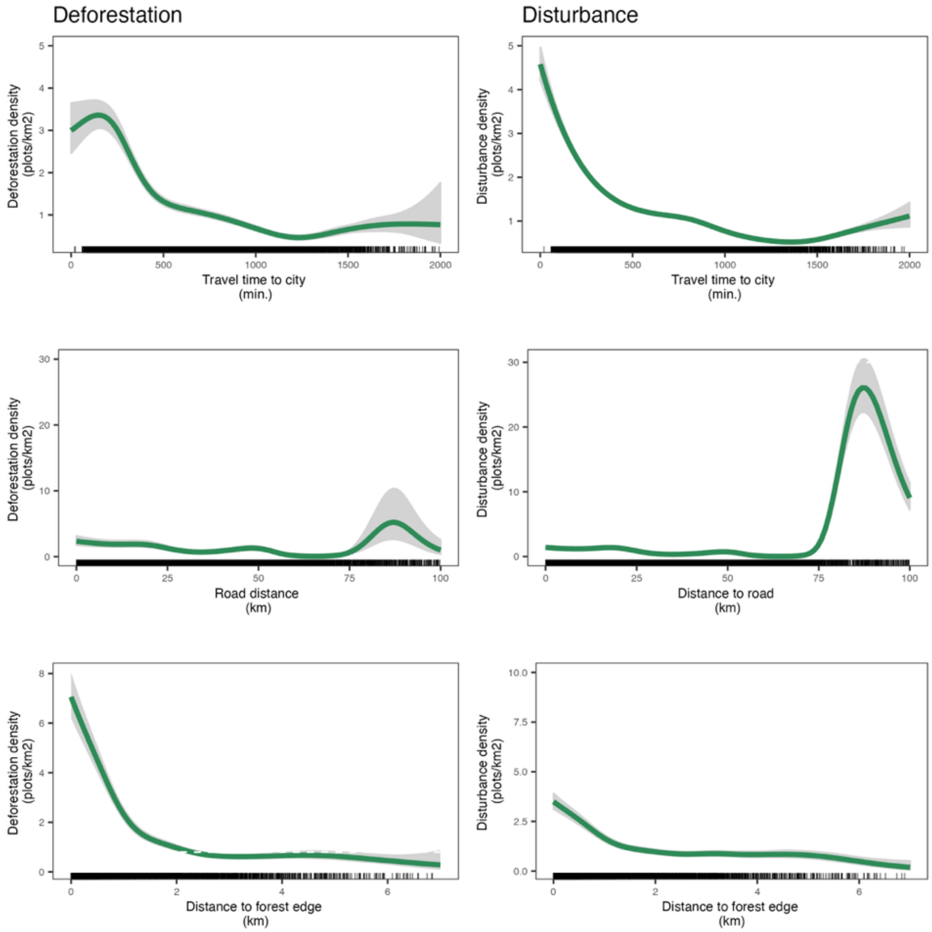
Local deforestation, disturbance, and values

At the local scale, we analyzed the spatial patterns of deforestation and disturbance in the Emberá Indigenous lands of Piriatí, Ipetí, and Balsas. The chosen models (Gaussian: exponential) had an explained deviance of 88.31% in deforestation density (AIC = 2083.82, Moran's I = -0.0024) and 72.76% in disturbance density (AIC = 2076.44, Moran's I = -0.0018). As the national scale analysis, these models included a spatial smooth to control for spatial autocorrelation and a random effect, which accounted for the variation among Piriatí, Ipetí, and Balsas. The random effects ($p > 0.5$) for both models and the spatial smooth in the deforestation model ($p < 0.05$) had lower importance (< 6%) than in the national scale models, which is expected given the reduced geographic area (Fig. 4; Appendices 3, 4). Relative to the national scale models, the distance to rivers and slope had greater importance (9–22%; $p < 0.001$; Appendix 7). Similarly, the distance to forest edge was significant ($p < 0.001$) and explained most of the deviance in the deforestation and disturbance models (51–41%; Fig. 4) and therefore is the focus of the local scale analysis (Fig. 6).

Deforestation density on average was approximately 9 plots/km² at the edge of forests, continuously dropped inside forest patches, and reached an oscillating minimum density after 1.5 km (~1 plot/km²). With lower magnitudes, disturbance density was ~ 5 plots/km² on the edge of forests, reached a minimum density at 1.2 km inside forest patches, and exhibited a moderate increase after 2.5 km (~ up to 4 plots/km²). As such, the spatial patterns of deforestation and disturbance at the local scale resembled those at the national scale and confirmed the limited spatial extent of land use and the relative stability of forest cover across Indigenous lands in Panama.

Participatory mapping at the local scale allowed the identification of the spatial patterns of three categories of values: (1) food from agriculture, (2) food gathering and household materials, and (3) relational. Mapping revealed that food from agriculture is produced near the *de* (home) and obtained from the *neu* (crops). These are rotational crops (2–3 years) of rice, maize, yam, and

Fig. 5. The effects of environmental and socioeconomic predictors on deforestation and disturbance density in Indigenous lands at the national scale during 2000–2020. A plot represents a ~30 m resolution pixel.

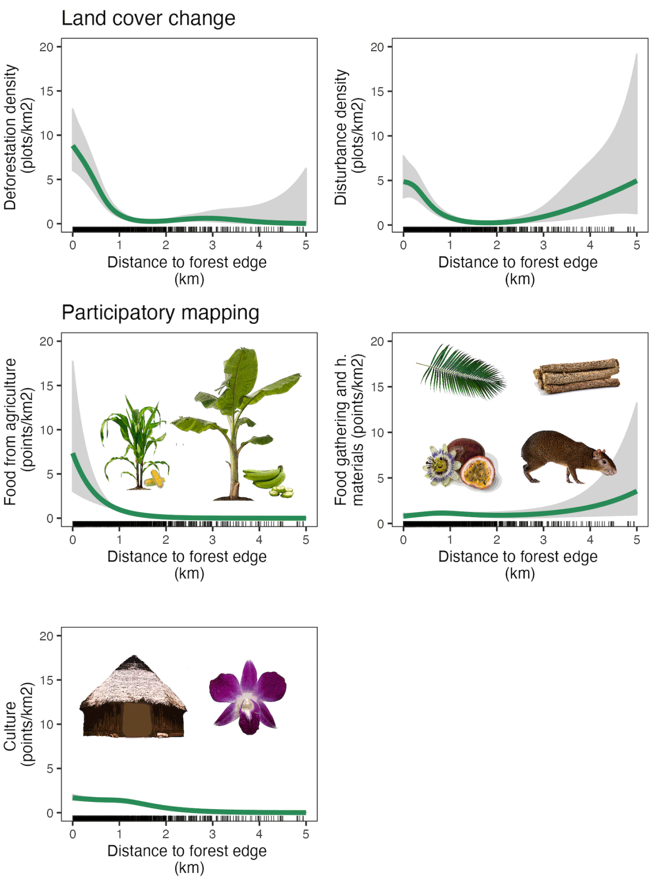


plantain for household consumption that are rotated through a fallow period (*pea*). Surplus agricultural production is a key source of income for educational expenses, medicines, clothing, and other household needs. The use of pesticides in some families, especially in the more accessible lands of Piriatí and Ipetí, has increased this agricultural surplus and even resulted in permanent rice plots. The spatial patterns of food from agriculture displayed the highest density (~7.5 points/km²) at forest edges and dropped to zero approximately at 1.5 km inside forest patches. These patterns approximately match the deforestation and disturbance densities (~9 and 5 plots/km², respectively) at forest edges on the same scale. Therefore, areas valued by the Emberá for food from agriculture correspond to the deforestation and disturbance events restricted to forest edges.

Compared to food from agriculture, food from gathering (e.g., fruits, honey, game, fish) and household materials (e.g., fibers, firewood, and timber) extend from de (home), *nea* (crop), and *pea* (fallow) to the *oi* (forest) and integrate different species and practices. For example, hunting agoutis (*Dasyprocta punctata*) may be accompanied by Trupa fruit gathering (*Oenocarpus mapora* Karst and *Oenocarpus bataua* Mart). Household materials such as *bálsamo* for house poles (*Myroxylon balsamum* Harms), *espavé* for canoes (*Anacardium excelsum* Bert. & Balb. ex Kunth), or *wagara* for thatching (*Sabal mauritiiformis* H. Wendl. ex Karts) are typically obtained about ~1–2 hours walking distance from the communities, although residents occasionally travel to more distant areas in their territories in the search for these products (Fig. 6). The varied species, practices, and locations of food gathering and household materials seem to result in a low density (~1 point/km²) inside forest patches and indicate that these values are widely dispersed in forests. Moreover, the slight increase at 3 km inside forest patches seems associated with the spatial patterns of disturbance density (Fig. 6). According to participatory mapping groups, occasional extractions of household materials throughout tributaries explain this slight density increase in forest patches. Overall, the spatial patterns related to food gathering and household materials differ from those for food from agriculture; whereas the latter occurs at higher densities on forest edges, the former occurs at low densities and is dispersed throughout the forests.

Relational forest values were associated with the Emberá way of life, identity, spirituality, and future. Regarding species, some were considered sacred because of their value in traditional medicine or the Emberá cultural identity, such as orchids from the

Fig. 6. The spatial patterns of deforestation, disturbance, and values regarding nature across forest patches at the local scale (Emberá Indigenous lands of Piriatí, Ipetí, and Balsas from eastern Panama). A plot represents a ~30 m resolution pixel derived from remote sensing. A point represents a location obtained through participatory mapping.



mountains or the widely dispersed kipara fruit (*Genipa americana* L.) for body painting. Regarding areas valued for the future of Embera's way of life, participatory mapping groups highlighted reforestation projects in the accessible lands of Ipetí and Piriatí. At the same time, those in the more remote Balsas pointed to their fallows and surrounding forests. Participatory mapping groups also pointed to landmarks such as abandoned settlements, old cemeteries, river reaches, and sacred mountains due to their historical meaning, connection to the ancestors, and being known to have sheltered *wandras* (spiritual entities). The latter usually implied traditional rules that discouraged accessing instrumental values (e.g., fishing or hunting) and were defined as *Drua Wandra*. The importance of specific landmarks may explain why relational values reached their maximum density next to rivers (3.8 points/km²) and at 40 degrees of slope (3 points/km²; Appendix 8). As in the case of food from gathering and household materials, the relational values were widely dispersed across forest patches (Fig. 6).

Although the local scale analyses exhibited common spatial patterns among Indigenous lands in eastern Panama, the LDA (linear discriminant analysis) and CCA (canonical correspondence analysis) indicated some differences. The LDA classified Indigenous lands based on outcome variables (i.e., deforestation, disturbance, and values) and predictors (i.e., environmental and socioeconomic; Appendix 9). The Balsas Indigenous land LDA displayed a 100% correct classification, implying that the outcome variables and predictors entirely separate this land in the Balsas watershed from the other two. In the case of Piriatí and Ipetí, the correct classification was 63.46% and 75%, respectively, and suggests an overlap between these Indigenous lands. These classifications imply that the outcome and predictor variables separate Indigenous lands by the Bayano (Ipetí and Piriatí) and Balsas watersheds.

Given the differences between Indigenous lands in the two watersheds, we used CCAs to compare the influence of predictors on outcome variables in Bayano and Balsas (Appendix 10). The CCA model for the Bayano watershed removed the slope from the analysis by forward selection. As a result, the cumulative proportion of variance explained by the first two canonical axes was 99.27%, and 94.86% corresponded to the first axis. Likewise, the variances explained for the Balsas watershed were 96.23% and 80.69%, and the forward selection procedure did not suggest the removal of any predictors. Thus, the slope influenced Balsas but not necessarily the Indigenous lands in the Bayano watershed. Other predictors had different loadings on the first axis, revealing additional differences between the two watersheds. For example, population density, road distance, and travel time to city had a higher loading in Bayano (-0.74, 0.67, 0.26, respectively) than in Balsas (-0.56, -0.51, -0.02). Conversely, the distance to rivers and the distance to forest edge had a higher loading in Balsas (-0.46, -0.91) than in Bayano (0.01, 0.73). Based on these results, we interpret that land use changes and values were primarily influenced by the socioeconomic predictors in Bayano, whereas the environmental predictors were more influential in the Balsas watershed.

DISCUSSION

Our study explores the spatial patterns of land use in Indigenous lands from Panama. Unlike previous studies focusing on deforestation, we integrate forest disturbances and Indigenous values regarding nature into our analysis. At the national scale, we found that the dominant cause of land cover change is disturbance in Indigenous lands and deforestation in other lands and protected areas. According to different environmental and socioeconomic predictors, deforestation and disturbance were spatially limited in Indigenous lands, explaining the stability of forest cover. We complemented this general perspective with a context-specific perspective at the local scale. To this end, we analyzed the relationship between deforestation and disturbance with instrumental and relational values regarding nature in three Emberá Indigenous lands. Based on participatory mapping, we found that food from agriculture mainly occurred where deforestation and disturbance wee more concentrated. In contrast, other instrumental and relational values were more dispersed in forests.

Land use at the national scale

The national scale results highlight that land cover change and stability display different trends among Indigenous lands, other lands, and protected areas. Disturbances followed by recovery have been the dominant cause of land cover changes in Indigenous lands, whereas deforestation is the dominant change in other lands, coinciding with estimates in the Amazon Basin (Walker et al. 2020). The prevalence of deforestation over degradation in protected areas bears more resemblance to estimates in other Central American countries (Bullock et al. 2020b). Additionally, our results directly quantify the extent of stable forest cover (i.e., undisturbed), which was two times higher in Indigenous lands than in other lands and protected areas.

Our focus on Indigenous lands reveals that socioeconomic predictors indicate specific areas where land cover changes have primarily occurred in these lands across Panama. We found that deforestation and disturbance in Indigenous lands for the past 20 years had moderate densities in the proximity to cities and were heavily concentrated in the least city and road accessible areas. These patterns are partially explained by Panama's land use history in which most agricultural development has been concentrated around cities in the southern dry pacific arc (Wright and Samaniego 2008). Unsurprisingly, cities' market pressures remain, and regarding Indigenous lands seem to have a larger disturbance effect than a deforestation effect. We suspect that cities' market pressures not only influenced Indigenous peoples' land use but also drove invasions that lead to deforestation of Indigenous lands (Vergara-Asenjo et al. 2017). Furthermore, the increasing concentration of deforestation and disturbance in rural areas with limited road accessibility mostly corresponds to the humid region of Darién in eastern Panama. A recent study suggests that multi-commodity trafficking by settlers in this region has driven recent land use changes, including the surroundings of Indigenous lands (Colectivo Darién 2021). These results highlight that deforestation and disturbance may display heterogeneous distributions that linear models might not detect, revealing distinctive land use legacies and pressures. Furthermore, we controlled for spatial autocorrelation, reducing biases when modeling deforestation and disturbance predictors (Mets et al. 2017).

The distance to forest edge, an environmental predictor, explains a common land use pattern in Indigenous lands associated with forest cover stability. Our results showed that deforestation and disturbance in Indigenous lands had a limited effect on forest patches. Specifically, we demonstrated that Indigenous land use exhibits a low density, spatial concentration on forest edges and temporal stability, explaining their relatively stable forest cover for the past 20 years. Participatory mapping during the 1980s in eastern Panama (Herlihy 1985, 1986) estimated that agriculture extended ~5 km from recently established Indigenous settlements. Because settlements partially define forest edges, our results suggest that these spatial patterns of Indigenous land use are persistent. These spatial patterns are also similar to those found by Coomes et al. (2022) in the Peruvian Amazon, where fallows (i.e., disturbances) around Indigenous settlements are more dispersed than in folk settlements. Furthermore, our combined national and local scale results are consistent with studies showing that Indigenous land use is relatively stable (Toledo et al. 2003, Paneque-Gálvez et al. 2013, Puc-Alcocer et al. 2019, Gray and Bilsborrow 2020, Coomes et al. 2022), reduces forest fragmentation (Cabral et al. 2018), and maintains biodiversity (Leung et al. 2019).

Indigenous land use and related forest values

Our local scale results suggest that food from agriculture, an instrumental value, is related to the spatial patterns of deforestation and disturbance on Indigenous lands. According to participatory mapping among the Emberá people, food from agriculture is related to deforestation and disturbance events on forest edges. Studies from folk and Indigenous communities in the Amazon basin have established that forests within 1.5–2 km from community settlements are typically dedicated to swidden agriculture, given the difficulties and costs of transporting agricultural produce (Jakovac et al. 2017, Coomes et al. 2022). Our results are similar: food production from agriculture among the Emberá is concentrated on forest edges, within < 2 km inside forest patches. Therefore, the most intensive and disruptive activities in forests correspond to food security and are limited by accessibility, partially explaining the stability of forest cover. Nevertheless, our results indicate that values regarding nature in Indigenous lands influence forest cover stability as well.

Compared to food from agriculture, our results showed that gathering activities for food and household materials are dispersed in forests. Hunting, fishing, harvesting of timber, and collection of non-timber forest products tend to occur at low densities up to 3 km from forest edges. These spatial patterns are consistent with previous studies showing that food from agriculture is integrated with other instrumental values in forests. For instance, collecting certain non-timber and timber forest products in Indigenous lands from the Neotropics occurs on fallows and disturbed forests (Velásquez Runk 2001, Dalle et al. 2002, Coomes 2004). Moreover, it's been found that > 20% of hunting events are opportunistic and related to agriculture and fishing (Smith 2008, Read et al. 2010). Our results indicate that food gathering and obtaining household materials, and thus, forest disturbances can also occur more than 3.5 km from forest edges. Similarly, hunting has been found to occur in forested areas within 5–6 km from communities and is heavily influenced by the proximity to rivers and tributaries (Read et al. 2010, Zayonc and Coomes 2022). Dalle et al. (2002) found that among the neighboring Kuna people in eastern Panama, tree and palm species preferred in household construction are associated with intact forests. According to our national and local estimates, the less deforested and disturbed forests (i.e., intact) are more likely to be found in the core of forest patches. Consequently, multiple instrumental values converge on forest edges, but the less disruptive values for forest cover (e.g., hunting, fishing, household materials) may extend toward forest patch cores.

The spatial patterns of relational values inform a broader understanding of Indigenous land use and forest cover stability. As for the instrumental values of food gathering and household materials, we found that relational values associated with Indigenous ways of life, identity, spirituality, and future were dispersed in forests and somewhat more frequent along riverbanks and high slopes. The patterns of relational values imply a lack of preference for unique species or habitats. Indeed, similar to the Anishnabee in the boreal forests of Canada (Berkes and Davidson-Hunt 2006), all elements from the Embera's land have some value and should be maintained for future generations. The association of relational values with landmarks such as rivers, mountains, rocks, or particular forest areas which, in some cases, are sacred and forbidden, concur with other studies about the Emberá (Koller-Armstrong 2008, Rosique-Gracia et al. 2020) and other Indigenous peoples (Berkes 2008). Santos-Granero (1998) defines these landmarks as "topograms" which represent the result of past human or spiritual transformative activities on the landscape. In our study, topograms seem to articulate well with the cultural identity of the Emberá and the traditional institutions that limit land use. By weaving general (i.e., national scale analysis) and context-specific perspectives (i.e., local scale participatory mapping), our results illustrate that it is not the exclusive influence of environmental and socioeconomic conditions that limit the expansion of deforestation and disturbance. Instead, the interplay of these conditions with diverse instrumental and relational values brings stability to forest cover.

Differences among Emberá lands

Our local scale results of the spatial patterns of land cover changes and values revealed differences between Indigenous lands in the Bayano and Balsas watersheds. Piriatí and Ipetí, in the Bayano watershed, are approximately 150 km away from the communities in the Balsas watershed and represent different land use histories. Located along the Panamerican Highway, Piriatí and Ipetí have been accessible to markets and, thus, subject to deforestation and disturbance pressures for more than 50 years (Wali 1993). Most of the Indigenous peoples in Piriatí and Ipetí inhabited other areas before the creation of the Bayano dam and were displaced to their current lands (Sharma et al. 2015). Ipetí's more rugged topography, among other predictors, may have reduced pressures on forests compared to Piriatí, but overall, both Indigenous lands were established in a deforested and disturbed landscape (Sharma et al. 2016). Like other Indigenous lands in the eastern province of Darién, Balsas have been subjected for decades to multiple social and cultural shocks, including religious missions, settler invasions, multi-commodity trafficking, and land tenure insecurity (Herlihy 2003, Colectivo Darién 2021). In fact, the Emberá in Balsas have been seeking a formal land title from the government for more than 30 years. These different land-use histories explain why participatory mapping in Ipetí and Piriatí emphasized food from agriculture over other instrumental values that would require extensive forest cover, in contrast to Balsas, which exhibited more diverse instrumental values. Furthermore, Ipetí and Piriatí were more likely to mention relational values linked to the future, such as reforestation projects (Sloan 2016, Shinbrot et al. 2022), as a way to restore their landscape and revitalize the Emberá ways of life. Participants in Balsas mapping mentioned more often relational values linked to topograms, such as sacred sites. Despite these differences, the prevalence of common Indigenous worldviews and values has positively influenced the current state of forests in these Indigenous lands, contingent on their history and surroundings.

Implications for equitable policies and lessons for landscape management

The prevalence of Indigenous worldviews and values supporting global values linked to climate change mitigation and biodiversity conservation suggests equitable policies and interventions. A fundamental policy incentive is to officially grant collective titles to Indigenous lands that lack them. This recognition of Indigenous land rights may imply that governments and private actors refrain from "productive" land uses (e.g., mining, monocultures), but represents a direct cost-effective action to avoid the social conflicts derived from development projects (Cansari and Gausset 2013, Sarrazin 2015) and land invasions (Vergara-Asenjo et al. 2017). Given Indigenous land use capacity to maintain more stable forest covers than other lands, granting official titles to Indigenous lands could represent direct instrumental values derived from forests to surrounding lands (e.g., water supply, pollination) in highly intervened landscapes, such as the Bayano watershed. In more intact landscapes, as in Balsas, granting official titles inside or near protected areas, would formalize Indigenous land stewardship actions to monitor and deter extractive activities in areas with irrecoverable carbon stocks and biodiversity. However, granting titles to Indigenous lands will only be effective when the right of land ownership is not exclusively articulated around so-called social functions, which may incentivize deforestation (Walker 2021) for establishing permanent agriculture, pasture, or timber extraction (Sarrazin 2015). This re-articulation of land ownership implies extending beyond a unidimensional and unidirectional valuation of the land toward recognizing plural worldviews and reciprocal forms to value nature, including those from Indigenous peoples. To guarantee long-term benefits, equitable incentives such as carbon offsets for reforestation actions (Holmes et al. 2017), land guardian programs (Reed et al. 2021), or recognizing Indigenous peoples as authorities in protected areas (Artelle et al. 2019) could have a synergistic effect with the recognition of land rights. Consequently, providing coherent and plural frameworks of land ownership, granting titles to Indigenous lands, and fostering equitable incentives to Indigenous peoples are pivotal for countries aiming to reach global climate (e.g., Nationally Determined Contributions; UNFCCC 2015) and biodiversity targets (e.g., 30X30 targets; CBD 2022).

Landscapes with limited land use, stable forest cover, and that provide diverse values, as the ones described in our study, have been suggested elsewhere. Based on negotiations with private actors and civil society organizations, the state of Acre (Brazil) developed in the 2000s an ecological-economic zoning that aimed to limit the areas for agriculture, sustainable use of forests, and strict forest conservation (Kainer et al. 2003). Subsequent policies supporting the ecological-economic zoning have proven effective in conserving forests and providing diverse values regarding nature (Alejo et al. 2022). Our findings resemble the TRIAD zoning in Québec (Canada), which has been implemented for forest management by dividing territories into three zones: a conservation zone to preserve biodiversity and ecological functions, an ecosystem management zone that is ecologically resilient with moderate human use, and a wood production zone (Messier et al. 2009). These initiatives suggest a potential consensus among different worldviews (Indigenous, government, private, civil society) to acknowledge the importance of landscape management to guarantee diverse values regarding nature. According to our findings, sustainable landscape management should not only emerge from the interest to guarantee instrumental values, but also relational values.

Caveats

We identified three caveats to consider in our study. First, we urge caution in interpreting forest disturbance in our results. Forest disturbance is usually associated and often confounded with "degradation," a concept defined in more than 50 different ways across the sciences (Ghazoul et al. 2015). In ecology, degradation is defined as a state of arrested succession and recovery that reduces ecological functionality (Ghazoul and Chazdon 2017). Considering that the detection of forest disturbances in our study involved the loss and recovery of some spectral attributes, we cannot establish that those changes necessarily imply forest degradation from an ecological perspective. Second, our national and local models better explained deforestation than forest disturbance. Including additional predictors may shed further light on the differences between land cover changes.

Finally, we used participatory mapping to interpret land use dynamics and forest cover stability from a context-specific perspective, focusing on local values regarding nature. In practice, the mapped categories of instrumental and relational values may overlap and extend beyond physical space. For instance, the act of building a canoe is interpreted here as a forest disturbance linked to an instrumental value (i.e., household material for transportation), which is more likely to occur near forest edges. Nevertheless, building a canoe for the Emberá also relates to non-spatial relational values, such as representing a cultural symbol of gender relationships or an act of transformation requiring the canoe builder to aid the dying tree spirit to safely pass a new state (Kane 1994). While participatory mapping has become a prevalent method for deliberation among stakeholders and appropriation by Indigenous peoples (Voisin et al. 2022), we recognize that the mapped values are perceived in different ways and extend to non-physical, social, and cultural spaces. Future studies could explore this potential fluidity and overlap among instrumental, relational, and intrinsic values (Pascual et al. 2017), and the differences in values perceptions concerning gender (Sharma et al. 2015), age (Vélez and López 2013), seasonality, and occupation (Asatrizy-Kumua et al. 2020).

CONCLUSION

The state of tropical forests in Indigenous lands exemplifies complex social-ecological systems in which land use dynamics emerge as a reflection of local needs and values regarding nature. A growing number of studies have controlled for the influence of socioeconomic and environmental conditions to gauge the net effect of Indigenous lands on forest conservation (Vergara-Asenjo and Potvin 2014, Blackman and Veit 2018, Alejo et al. 2021, Sze et al. 2022). Our study provides a complementary contribution by analyzing the influence of socioeconomic and environmental predictors on Indigenous land use. We conclude that understanding Indigenous land use in tropical forests implies broadening the scope of analysis beyond deforestation to examining the spatial heterogeneity of forest disturbances and local values regarding forests. Our study shows that Indigenous land use is more likely to cause temporal disturbances than deforestation, and these changes are spatially restricted and temporarily stable. These patterns reflect instrumental and relational values: agriculture for food production is concentrated on forest edges, whereas gathering food and household materials, and relational values are dispersed throughout forests. Taken together, these results illustrate that diverse values regarding nature, in this case, framed by Indigenous worldviews, can beget stability to forest cover, contributing to Indigenous peoples' quality of life, climate change mitigation, and biodiversity conservation. To align these contributions with global climate and biodiversity targets, it is crucial to disarticulate land ownership from deforestation, grant titles to Indigenous lands, and foster equitable incentives to Indigenous peoples.

Author Contributions:

CA, CP, BL, and OC developed the idea for this study. CA and MO collected the field data. CA processed geospatial data and performed the statistical analysis. CA wrote the first draft of the manuscript, and all other co-authors contributed to revising and improving the submitted version. All authors contributed to the article and approved the submitted version.

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Data Availability:

The code that supports the findings of this study is openly available in the Open Science Framework at https://osf.io/fwsb2 (doi:10.17605/OSF.IO/FWSB2). None of the data are publicly available because this research was performed in collaboration with Indigenous peoples and will first require the permission of the Traditional Authorities. If such permission is granted, the data may be made available by the corresponding author (CA). Ethical approval for this research study was granted by McGill University Research Ethics Board (File Number: 21-03-023).

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Appendix 1. Estimated accuracies from the land-cover change detection obtained through CODED in Google Earth Engine.

	Stable forest	***Stable non-forest***	***Deforestation***	***Disturbance***
User's accuracy	*91.59*	*90.20*	*80.00*	*76.67*
Producer's accuracy	*90.93*	*95.74*	*73.33*	*60.52*
Overall accuracy				*90.05*

Appendix 2. General models tested to explain the spatial patterns of deforestation, disturbance, and values regarding nature in Panama's forests.

	Equation
National and local scale models	$log(density_i) = b_0 + f_1(S_1, i) + f_2(S_2, i) + \cdots f_n(S_n, i) + log(forest2000) + b_m + f(lon_i, lat_i)$

Where $density_i$ represents deforestation or, disturbance, or values density per km2 in a grid cell i, and f are smooth functions on n number of predictors S. b_m and $f(lon_i, lat_i)$ represent the random effects and spatial smooth, respectively. For each scale (i.e., National and Local) and outcome variable (deforestation, disturbance, and values), we tested three spatial smooth functions $f(lon_i, lat_i)$: spheric splines, Duchon splines, and a gaussian process with exponential correlation (Wood, 2017).

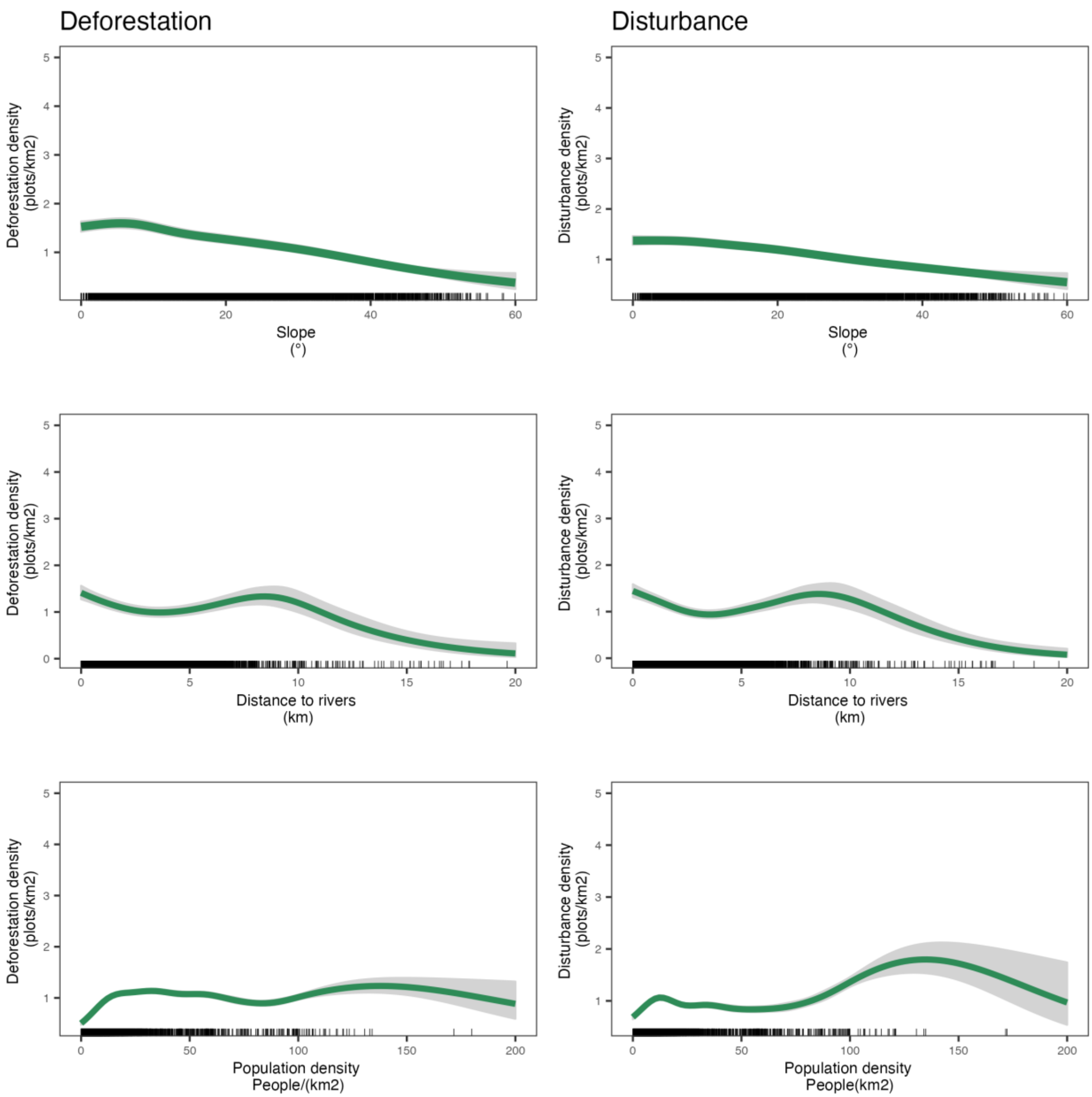
Appendix 3. Models tested to infer the spatial patterns of deforestation, disturbance, and values regarding nature at the national and local scale.

Scale	Outcome variable	Spatial Correlation function	Deviance Explained %	AIC	Moran's I	p Value
National	Deforestation density (plots/km2)	Sphere splines	74.66	450049.94	0.0263	0.000
		Duchon splines	75.38	448303.22	0.0202	0.000
		Gaussian: Exponential	75.39	448268.13	0.0198	0.000
National	Disturbance density (plots/km2)	Sphere splines	64.81	271222.36	0.0079	0.000
		Duchon splines	65.22	270593.18	0.0067	0.000
		Gaussian: Exponential	65.17	270685.59	0.0063	0.000
Local	Deforestation density (plots/km2)	Sphere splines	88.37	2093.04	-0.0025	0.867
		Duchon splines	88.37	2093.04	-0.0025	0.867
		Gaussian: Exponential	88.68	2083.82	-0.0024	0.852
Local	Disturbance density (plots/km2)	Sphere splines	72.45	2079.51	-0.0026	0.880
		Duchon splines	72.45	2079.51	-0.0026	0.880
		Gaussian: Exponential	73.42	2076.44	-0.0018	0.737
Local	Food from agrilculture (points/km2)	Sphere splines	81.13	545.07	0.0202	0.000
		Duchon splines	81.84	542.15	0.0220	0.000
		Gaussian: Exponential	82.06	542.51	0.0219	0.000
Local	Food from gathering and household materials (points/km2)	Sphere splines	39.13	1430.07	-0.0018	0.750
		Duchon splines	39.61	1427.59	-0.0018	0.738
		Gaussian: Exponential	39.73	1428.62	-0.0018	0.757
Local	Culture (points/km2)	Sphere splines	30.22	503.27	0.0012	0.049
		Duchon splines	30.52	504.20	0.0011	0.058
		Gaussian: Exponential	30.52	505.99	0.0009	0.078

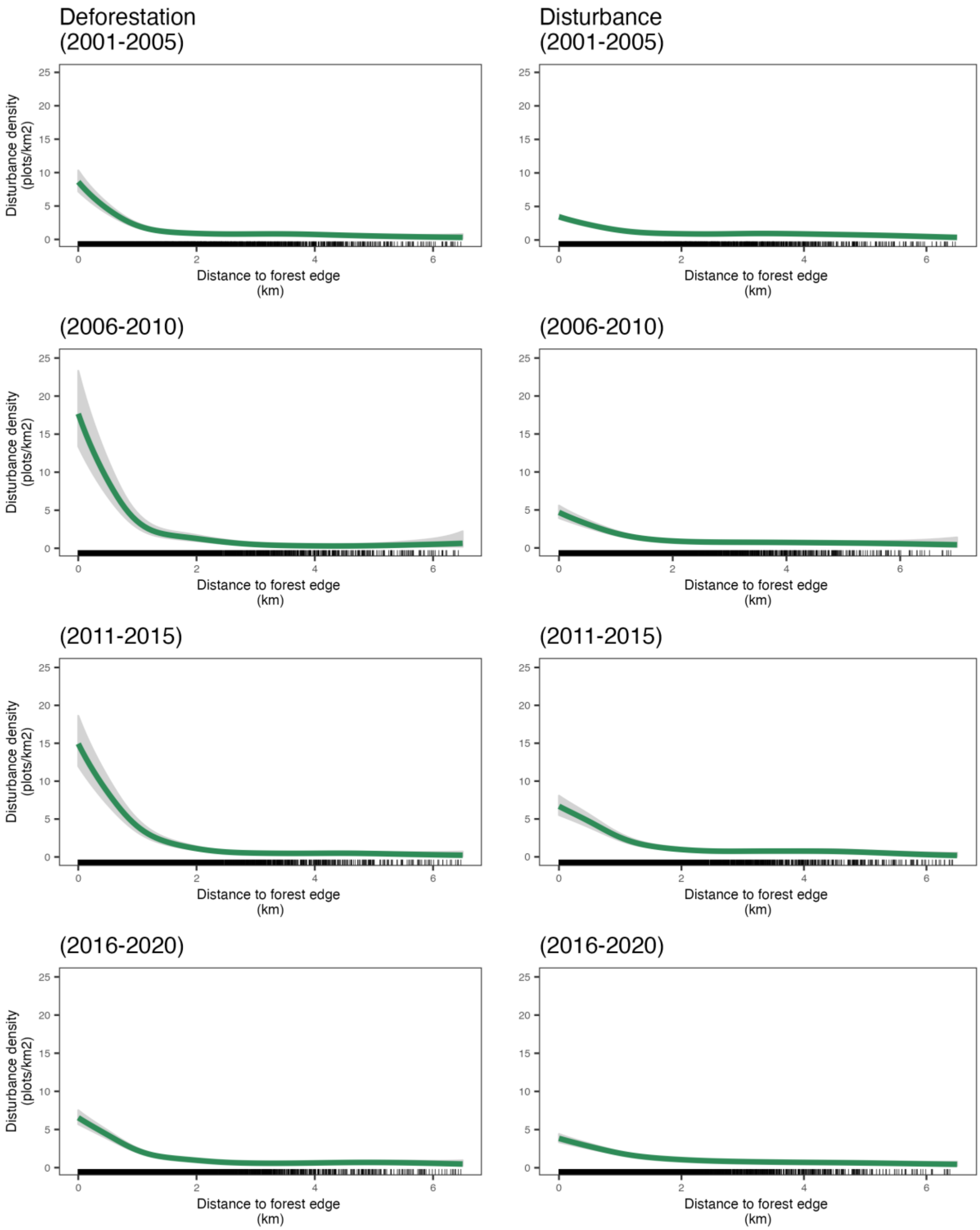
Appendix 4. Variables significance for models inferring the spatial patterns of deforestation, disturbance, and values regarding nature at the national and local scale.

Scale	Outcome	Variable	p-value
National	Deforestation density (plots/km2)	Slope	0.000
		Distance to rivers	0.000
		Distance to forest edge	0.000
		Travel time to city	0.000
		Population density	0.000
		Distance to roads	0.000
		Spatial smooth	0.000
		Random effects	0.000
	Disturbance density (plots/km2)	Slope	0.000
		Distance to rivers	0.000
		Distance to forest edge	0.000
		Travel time to city	0.000
		Population density	0.000
		Distance to roads	0.000
		Spatial smooth	0.000
		Random effects	0.000
Local	Deforestation density (plots/km2)	Slope	0.000
		Distance to rivers	0.001
		Distance to forest edge	0.000
		Travel time to city	0.011
		Population density	0.044
		Distance to roads	0.641
		Spatial smooth	0.043
		Random effects	0.669
	Disturbance density (plots/km2)	Slope	0.000
		Distance to rivers	0.000
		Distance to forest edge	0.000
		Travel time to city	0.003
		Population density	0.002
		Distance to roads	0.059
		Spatial smooth	0.001
		Random effects	0.534
	Food from agriculture (plots/km2)	Slope	0.153
		Distance to rivers	0.225
		Distance to forest edge	0.000
		Travel time to city	0.001
		Population density	0.199
		Distance to roads	0.834

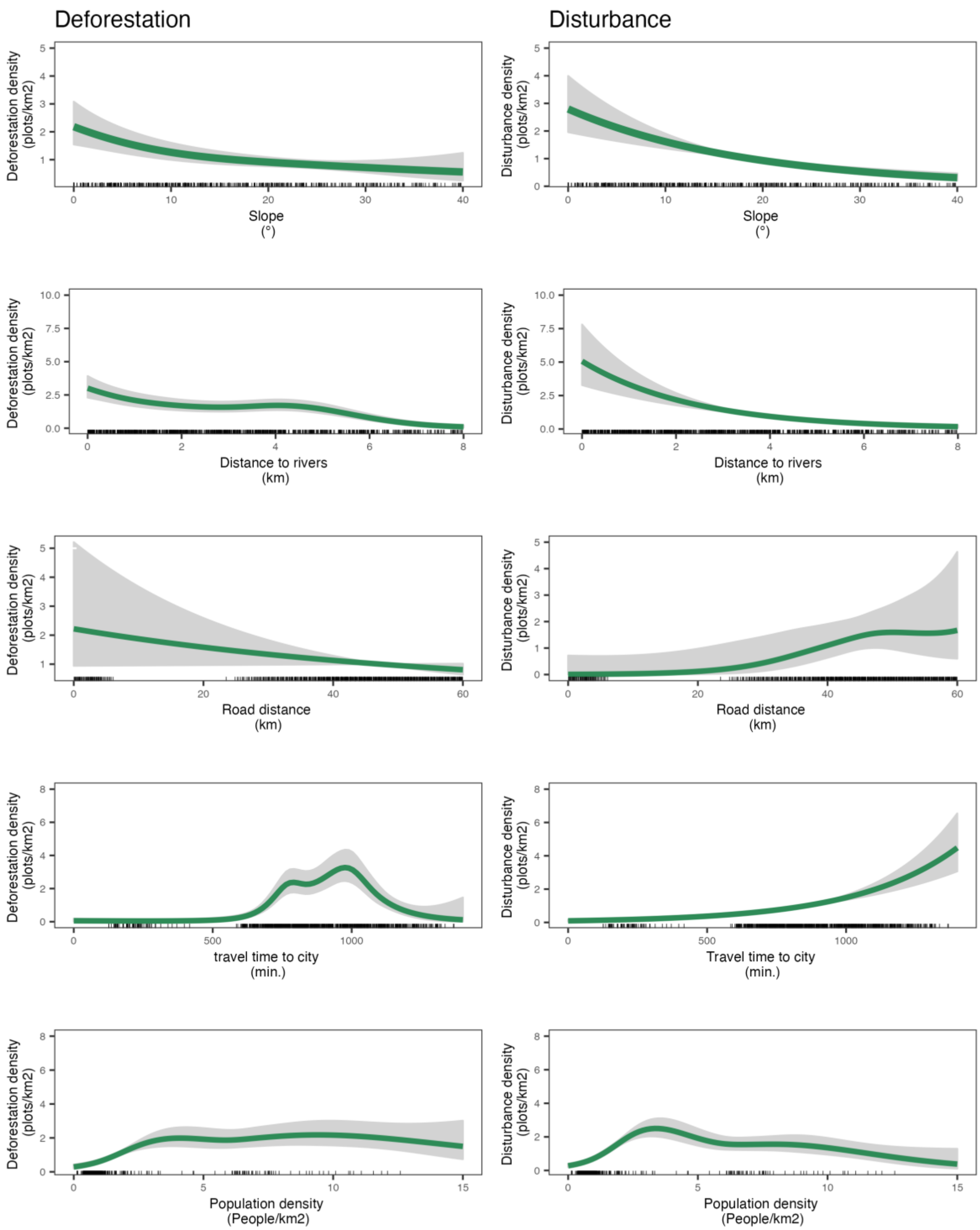
Appendix 5. The effects of environmental and socio-economic predictors on deforestation and disturbance density in Indigenous Lands at the national scale during 2000-2020.



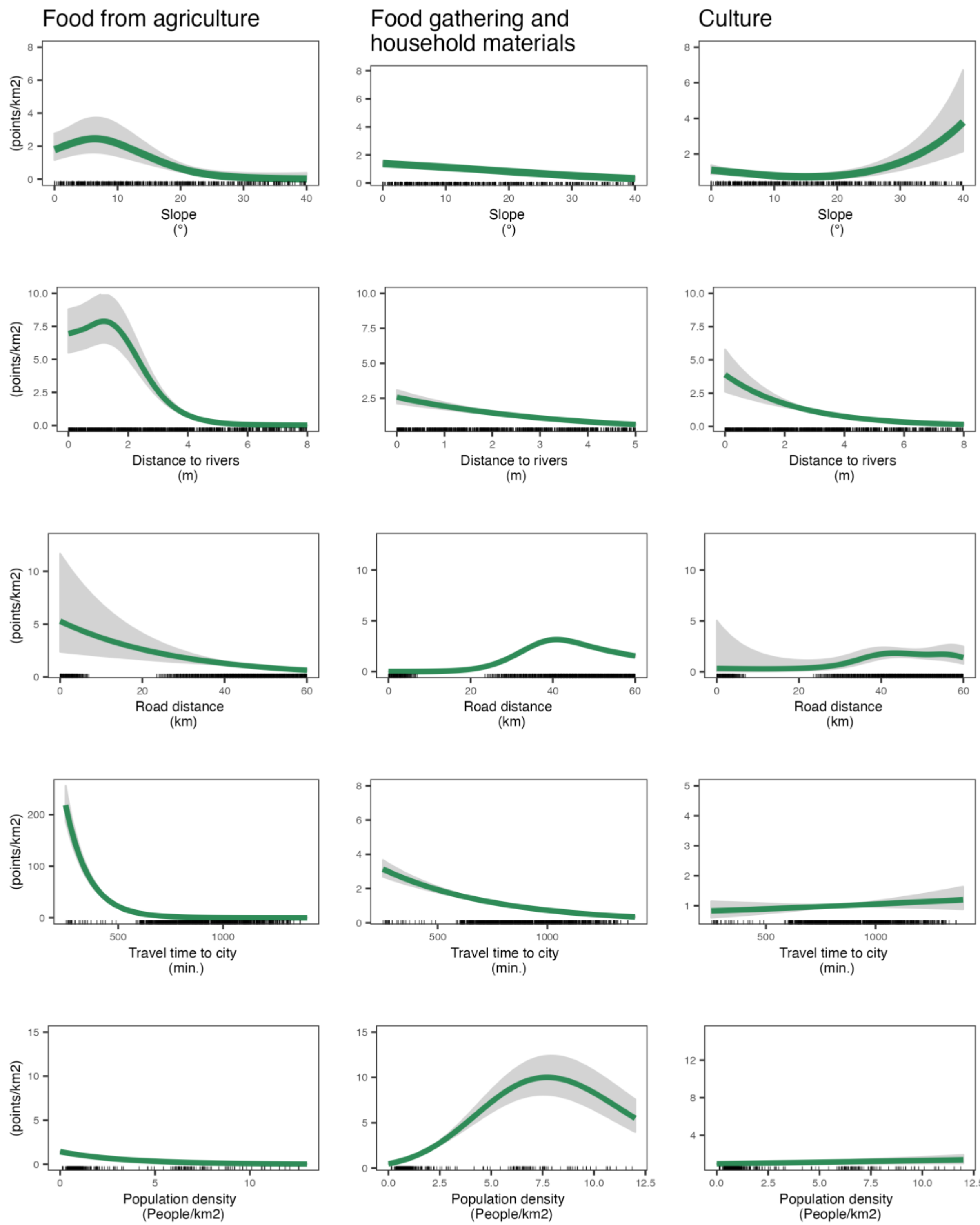
Appendix 6. The effects of the distance to forest edge on deforestation and disturbance density in Indigenous Lands at the national scale in 4 subperiods between 2001-2020.



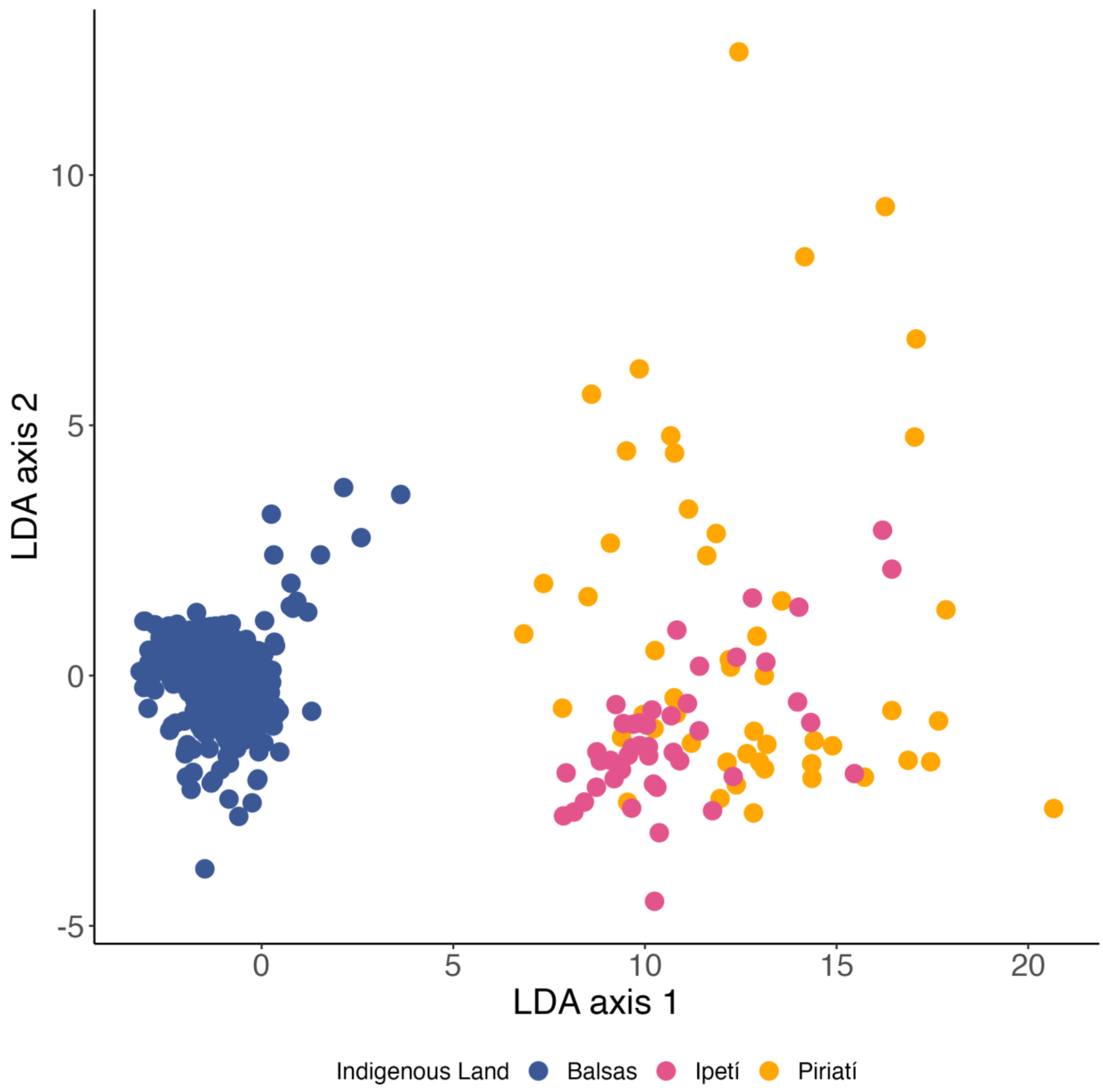
Appendix 7. The effects of environmental and socio-economic predictors on deforestation and disturbance density at the local scale during 2000-2020. The local scale corresponds to the Indigenous Lands of Piriatí, Ipetí, and Balsas in eastern Panama.



Appendix 8. The effects of environmental and socio-economic predictors on values regarding forests at the local scale. The local scale corresponds to the Indigenous Lands of Piriatí, Ipetí, and Balsas in eastern Panama.

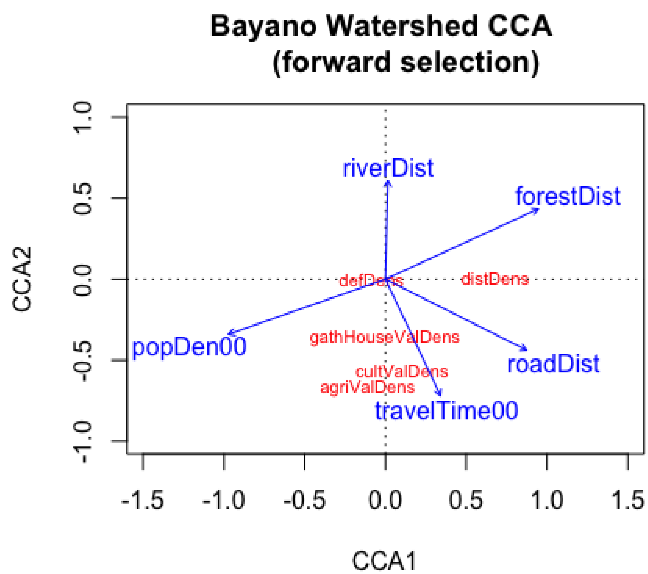


Appendix 9. Linear discriminant analysis (LDA) grouping Indigenous Lands at the local scale (i.e., Piriatí, Ipetí, and Balsas) based on a matrix of outcome variables and environmental and socio-economic predictors.

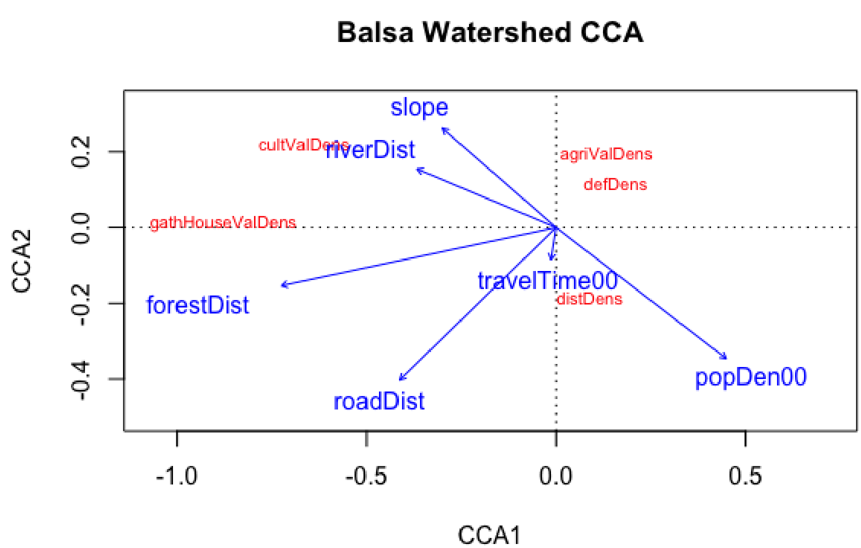


Appendix 10. Biplots of canonical correspondence analysis (CCA) between land cover changes and values regarding forests (red) (outcome variables) with socio-economic and environmental predictors (blue) (explanatory variables).

A



B



A. The Bayano Watershed (Indigenous Lands of Piriatí and Ipetí) and B. The Balsas Watershed (Indigenous Land of Balsas). defDens represents deforestation density and distDens represents disturbance density. The values in forests are agriValDens, representing food from agriculture density; gathHouseValDens, representing food gathering and household materials density; and cultValDens, representing cultural values.