Domestic forests in the neotropics: Stability for climate change mitigation and other nature's contributions to people.

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Thesis Abstract

The stability of forests' cover and carbon stocks (i.e., stable magnitude, spatial extent, and temporal longevity) is crucial to mitigate the effects of climate change, protect biodiversity, and provide other nature's contributions to people. In the neotropics, the fate of forests is strongly associated with Indigenous Peoples and Local Communities (IPLC) that have inhabited a considerable part of these ecosystems for decades to millennia. IPLC display distinct worldviews and values regarding nature that have resulted in processes of active landscape management. Due to this inherent influence on the landscape, IPLC's forests have been defined as domestic forests. Furthermore, IPLC domestic forests have been the subject of external interventions such as the establishment of Protected Areas (PAs) and financial incentives for Reducing Emissions from Deforestation and Degradation (i.e., REDD+). Given domestic forests' potential contribution to climate change mitigation and other nature's contributions to people, understanding the interplay between IPLC's inherent worldviews, values, and management with external policy interventions is of the utmost importance. Previous research has focused on the effect of IPLC and related policy interventions on avoiding deforestation. Nevertheless, few studies have explored IPLC's inherent influence on forest stability indicators. To address these gaps, this thesis aimed to answer the question: how do IPLC's land tenure, external policy incentives, and local values influence forest cover and carbon stocks stability in the neotropics?

The first and second chapters relied on remote sensing and quasi-experimental methods to estimate IPLC effects on forest conservation. Concretely, the first chapter aimed to estimate the temporal and spatial effects of three land tenure regimes on aboveground carbon stocks in Panama and four Amazon Basin countries. The results showed that Indigenous Lands, including their overlaps with Protected Areas, harbor more stable and higher carbon stocks than private/public lands without protection and are as effective as Protected Areas. To further understand the diversity of governance systems in Protected Areas and incentives to avoid land-use emissions, Chapter 2

aimed to assess the effects of Protected Areas managed by Local Communities (i.e., Community Managed Protected Areas) on carbon stocks dynamics before and after the adoption of REDD+ programs. The results showed that Community Managed Protected Areas in Petén (Guatemala) and Acre (Brazil) effectively maintained carbon stocks and avoided land use emissions after REDD+ was implemented. Moreover, Community Managed Protected Areas' effectiveness in forest conservation was relative to private/public lands without protection and other PAs.

Using remote sensing and participatory mapping, the last chapter delved into analyzing the spatial patterns of land use and values regarding nature in Indigenous Lands from Eastern Panama. Indigenous land use was more likely to cause disturbances than deforestation, and these land use changes were spatially and temporally restricted, bringing stability to forest cover. Furthermore, land use and, thus, forest cover stability were linked to a worldview that integrates diverse instrumental and relational values regarding nature in landscape management. Taken together, my thesis indicates that IPLC rely on a concentrated area for land use, usually accessible lands, allowing for forest core areas to remain stable both spatially and temporally. Thus, IPLC's forests at the neotropical scale represent a cornerstone for policies related to climate change mitigation, forest conservation, social wellbeing, and other nature's contributions to people.

Résumé de thèse

La stabilité du couvert forestier et des stocks de carbone (**c.-à-d. stabilité de l'ampleur, de l'étendue spatiale et de la longévité temporelle)** est cruciale pour atténuer les effets du changement climatique, protéger la biodiversité, et fournir d'autres contributions de la nature aux populations. Dans les régions néotropicales, le sort des forêts est fortement associé aux Peuples Autochtones et des Communautés Locales qui habitent une partie considérable de ces écosystèmes depuis des décennies, voir des millénaires. Les Peuples Autochtones et des Communautés Locales ont des visions

du monde et des valeurs particulières concernant la nature qui ont donné lieu à des processus de gestion active du paysage. En raison de cette influence inhérente sur le paysage, les forêts des Peuples Autochtones et des Communautés Locales ont été définies comme des forêts domestiques. Par ailleurs, les forêts domestiques des peuples autochtones et des communautés locales ont été l'objet d'interventions externes telles que la création de Aires Protégées et d'incitations financières pour la réduction des émissions dues à la déforestation et à la dégradation (c.-à-d., REDD+). Étant donné la contribution potentielle des forêts domestiques à l'atténuation du changement climatique et des autres contributions de la nature aux personnes, il est de la plus haute importance de comprendre l'interaction entre les visions du monde, les valeurs et la gestion inhérentes des Peuples Autochtones et des Communautés Locales avec les interventions politiques externes. Des recherches précédentes aient été menées sur l'effet des Peuples Autochtones et des Communautés Locales et des interventions politiques liées à la déforestation. Néanmoins, peu d'études ont exploré l'influence inhérente des Peuples Autochtones et des Communautés Locales sur les indicateurs de stabilité des forêts. Pour combler ces lacunes, cette thèse vise à répondre à la question suivante : comment les régimes fonciers des Peuples Autochtones et des Communautés Locales, les incitations politiques externes et les valeurs locales influencent-ils la stabilité du couvert forestier et des stocks de carbone dans les régions néotropicales?

Le deux premieres chapitres s'appuient sur la télédétection et des méthodes quasi-expérimentales pour estimer les effets des Peuples Autochtones et des Communautés Locales sur la conservation des forêts. Concrètement, le premier chapitre vise à estimer les effets temporels et spatiaux de trois régimes fonciers sur les stocks de carbone au Panama et dans quatre autres pays du bassin amazonien. Les résultats montrent que les Terres Autochtones, y compris lorsqu'ils chevauchent des Aires Protégées, montrent des stocks de carbone plus stables et plus élevés que les terres privées/publiques sans protection. De plus, ces terres soient aussi efficaces que les Aires Protégées. Pour mieux comprendre la diversité des systèmes de gouvernance dans les Aires Protégées, et les incitations à éviter dû aux émissions liées à l'utilisation des terres, le deuxième chapitre vise à évaluer les effets des Aires Protégées gérées par les Communautés Locales sur la dynamique des stocks de carbone avant et après l'adoption des programmes REDD+. Les résultats montrent que les Aires Protégées gérées par les communautés à Petén (Guatemala), et à Acre (Brésil), maintiennent efficacement les stocks de carbone et évitent les émissions liées à l'utilisation des terres après la mise en œuvre du programme REDD+. En outre, l'efficacité des zones protégées gérées par la communauté en matière de conservation des forêts était relative aux terres privées/publiques sans protection et aux autres Aires Protégées.

À l'aide de la télédétection et de la cartographie participative, le dernier chapitre a analysé les schémas spatiaux d'utilisation des terres et les valeurs concernant la nature dans les Terres Autochtones du Panama oriental. L'utilisation des terres autochtones était plus prédisposé à entraîner des perturbations que la déforestation, et ces changements étaient spatialement et temporairement limités, apportant une stabilité à la couverture forestière. En outre, l'utilisation des terres et, par conséquent, la stabilité du couvert forestier étaient liées à une vision du monde qui intègre diverses valeurs instrumentales et relationnelles concernant la nature dans la gestion du paysage.
Dans l'ensemble, ma thèse indique que les Peuples Autochtones et des Communautés Locales dépendent d'une zone concentrée pour l'utilisation des terres, généralement des terres accessibles, ce qui permet aux noyaux forestiers de rester stables tant spatialement comme temporellement. Ainsi, les forêts domestiques des Peuples Autochtones et des Communautés Locales, à l'échelle néotropicale représentent une pierre angulaire pour les politiques liées à l'atténuation du changement climatique, à la conservation des forêts, au bien-être social et d'autres contributions de la nature aux populations.

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Contribution to original knowledge

Improving conservation and management actions of neotropical forests is one of the most important contributions to limiting global warming to 1.5°C. These actions heavily rely on Indigenous Peoples and Local Communities (IPLC) that have traditionally managed and domesticated neotropical forests for decades to millennia. Previous studies have either focused on determining IPLC lands' effect on avoided deforestation for a single time period (i.e., temporal effect) or how deforestation reduces within their boundaries (i.e., spatial effect) on a national or subnational scale. The first chapter builds upon these studies and estimated both the temporal and spatial effects of Indigenous Lands and their overlaps with Protected Areas (PAs) on aboveground carbon stocks in Panama and four Amazon Basin countries. In this chapter, I used matching analysis to control for agriculture suitability and market access covariates to estimate the annual effects of Indigenous Lands and PAs on carbon stocks relative to unprotected lands (i.e., temporal effects) for fourteen years. Furthermore, I explored the spatial heterogeneity of these annual effects (i.e., spatial effects) on carbon stocks inside Indigenous Lands and PAs boundaries relative to unprotected lands using geographic discontinuity designs. Consequently, this chapter makes a novel contribution to research by integrating matching analysis and geographic discontinuity designs to test the effectiveness of Indigenous Lands and PAs in conserving carbon stocks. After controlling for spatial location, our results established that Indigenous Lands in neotropical forests contribute to the stability of carbon stocks through time and space.

To account for the diversity of Protected Areas categories, including those managed by Local Communities (i.e., Community Managed PAs), and policy incentives to avoid land-use emissions, Chapter 2 aimed to assess the effectiveness of Community Managed PAs on forest carbon stocks dynamics before and after the adoption of REDD+ programs in Petén (Guatemala) and Acre (Brazil). Compared with studies that estimate PAs' effectiveness using unprotected lands or other PAs as counterfactuals, I estimated Community Managed PAs’ effectiveness relative to multiple land tenures and controlling for market access and agriculture suitability covariates. Moreover, I explored this effectiveness temporally and spatially on carbon stocks dynamics, contrasting similar studies that usually explore the former or the latter on avoided deforestation. Temporally, we analyzed carbon stocks dynamics before and after REDD+ initiatives began to operate and exhibited the limited effects of this policy incentive at the subnational scale. Spatially, we compared carbon stocks dynamics inside and around the boundaries of Community Managed PAs and identified moderate reductions in land-use emissions and no evidence of leakage after REDD+ was implemented.

Based on the inherent capacity of IPLC lands to maintain stable carbon stocks, the third chapter explores the potential values linked to land use and forest cover stability in IPLC lands. Specifically, I analyze deforestation and disturbance spatial-temporal patterns in Indigenous Territories and Other unprotected Lands in Panama. While similar studies have typically relied on linear models to explain deforestation patterns, I focus on non-linear interactions to quantify where deforestation, and the less explored forest disturbances, are concentrated, dispersed, or even absent. Following this non-linear analysis, I performed participatory mapping across three Indigenous Lands in eastern Panama to identify instrumental (e.g., food) and relational (e.g., culture) values related to land use. Based on participatory mapping, I quantify the spatial patterns of instrumental and relational values linked to Indigenous land use, revealing circumstances involved in forest cover stability. Taken together, the most relevant contribution of my thesis concerns the focus on IPLC lands' capacity to bring stability to carbon stocks and forest cover in neotropical forests and, therefore, contribute to global climate change mitigation and biodiversity conservation.

Contribution of Authors

I am the primary author of all the studies included in this thesis. I formulated the research questions, hypotheses, and methodologies, performed data curation and collection (sometimes in collaboration with others, as explained below), analyzed the data, and wrote the manuscripts. Prof. Catherine Potvin supervised the conceptual framework, methods, interpretation of the results, and writing of all the manuscripts included in this thesis.

Chapter 1

Wayne S. Walker, Seth R. Gorelik, Carmen Josse, Jose Luis Aragon-Osejo, Sandra Rios, Cicero Augusto, Andres Llanos, and Catherine Potvin participated in data curation. Catherine Potvin and Oliver T. Coomes supervised the findings of this chapter. All authors contributed to the manuscript revision, read, and approved the published version in PLOS ONE.

Chapter 2

Wayne S. Walker, and Seth R. Gorelik participated in data curation. Catherine Potvin supervised the findings of this chapter. All authors contributed to the manuscript revision, read, and approved the published version in Frontiers in Forests and Global Change.

Chapter 3

Manuel Ortega participated in data collection and curation. Catherine Potvin, Brian Leung, and Oliver T. Coomes supervised the findings of this chapter. All authors contributed to the manuscript revision, read, and approved the contents of this chapter.

General Introduction

Limiting global warming to 1.5°C demands ambitious societal changes and policy interventions (Matthews & Wynes, 2022). Some of these changes and interventions must address land-use emissions, which after fossil fuel emissions, have represented the most significant contribution to the increases in the global temperature (Matthews et al., 2014). The neotropics (Tropical Americas) are particularly relevant for land-use emissions because forests store nearly twice the amount of carbon found in tropical Africa and Asia (Saatchi et al., 2011). Moreover, the neotropics have registered the highest net change in carbon losses from land use, caused mainly by disturbances of forests that remain forests and, to a lower extent, caused by deforestation (Baccini et al., 2017a). Commercial and subsistence agriculture are the leading causes of deforestation, whereas the extraction of timber and fuelwood are the leading causes of forest disturbances (Hosonuma et al., 2012).

Given the link between deforestation and forest disturbances with climate change, it has been proposed to increase carbon sequestration and reduce land use emissions through the restoration, conservation, and improved management practices in natural ecosystems referred to as Natural Climate Solutions (Griscom et al., 2017). Among these solutions, the potential of restoring natural ecosystems (e.g., reforestation, afforestation) is limited compared to conserving and improving the management of existing forests (Walker et al., 2022). More precisely, the most significant climate change mitigation benefits do not result from promoting carbon stocks' recovery after events of deforestation and disturbance but result from maintaining forests' stable carbon stocks (Dooley et al., 2022). Thus, global Natural Climate Solutions must necessarily develop management and conservation actions targeting carbon stocks' stability in the neotropics.

Carbon stocks' stability which refers to maintaining magnitude, spatial extent, and temporal longevity, is linked to ecological stability (Keith et al., 2021). Among the different forms of ecological integrity, ecological stability is related to ecosystem's capacity to withstand and recover from natural and human perturbations by maintaining stable dominant ecological characteristics in terms of composition (e.g., taxonomic and functional diversity), structure (e.g., ecosystem extent, connectivity), and function (e.g., phenology, biomass) (Roche & Campagne, 2017). In other words, ecosystem's capacity to defy change and remain stable and resilient (McCann, 2000). For instance, at the ecosystem scale, a diverse community composition with species of varied traits is expected to confer resilience and adaptation to a changing environment, driving ecosystem stability (Cleland, 2011). This implies that forests unable to maintain stable ecological characteristics in the face of natural or human perturbations will lose integrity and, thus, result in carbon stocks losses that may be irrecoverable in the time frame of emissions reduction targets (Noon et al., 2022). Conversely, forests involving management and conservation actions that maintain ecological stability regarding compositional, structural, and functional aspects of biodiversity will result in stable carbon stocks that are less prone to atmospheric emissions. Hence, natural climate solutions aiming for carbon stock's stability largely depend on maintaining forests' ecological stability. At the same time, carbon stocks dynamics represents one of the multiple indicators of ecosystem functioning, however; this single indicator should not be confounded or considered equivalent to the multiple indicators and scales defining ecological stability (Pimm, 1984).

In the context of forest management and conservation actions for climate change mitigation, monitoring carbon stocks become as essential as monitoring deforestation and disturbances. Open remote sensing derived products (e.g., Hansen et al., 2013) relying on satellite imagery with moderate spatial resolution and high temporal resolution (e.g. Landsat mission) have increased the capacity to detect deforestation that along with conversion factors, usually derived from field inventories, allow making approximate estimates of carbon flows (Zhang et al., 2019). Other research efforts by integrating field inventories, spaceborne LiDAR, satellite imagery, and machine learning algorithms have developed wall-to-wall carbon maps across tropical forests (Avitabile et al., 2016; Saatchi et al., 2011). These remote sensing-derived products exhibit monitoring capacities that are limited to detecting the complete conversion of forest and estimating the magnitude and spatial distribution of carbon stocks and therefore are unable to detect forest disturbances and the temporal variability of carbon stocks.

More recently, the integration of remote sensing, artificial intelligence, and big data processing platforms has surpassed previous monitoring capacities. The detection of forest disturbances, that is, temporal changes in forest cover followed by recovery, has improved due to spectral mixture analysis, time series analysis of satellite imagery, and high spatial resolution products, some of which have open access through big data processing platforms like Google Earth Engine (Gao et al., 2020). Big data processing platforms coupled with machine learning algorithms have also improved the capacity to monitor carbon stocks across neotropical forests, allowing to detect the temporal variability and longevity of carbon stocks along with their magnitude and spatial extent in low and moderate spatial resolutions for the past two decades (Baccini et al., 2017b; Harris et al., 2021; Walker et al., 2020). These recently improved monitoring capacities represent an opportunity to identify which segments of the neotropics maintain stable forest covers (i.e., not deforested or disturbed) and carbon stocks with the greatest potential for forest management and conservation actions and other natural climate solutions.

Like other natural ecosystems in the globe, neotropical forest lands with the potential to provide climate change mitigation benefits are not necessarily private or public inhabited lands. In fact, 37% of the remaining natural lands on the globe are under the custody of Indigenous Peoples, that is, peoples and nations that have a historical continuity with societies before invasion and colonization with distinctive social, cultural, economic, and political institutions (Garnett et al., 2018). In Neotropical countries, Indigenous Peoples are estimated to represent around 5% of the total population but account for nearly 10% of the population in heavily forested districts (Thiede & Gray, 2020). These estimates also suggest that around 5% of neotropical countries' total population that inhabit heavily forested districts are non-indigenous peoples. Part of this population segment can be defined as Local Communities that display traditional ties to natural ecosystems and do not necessarily self-identify as Indigenous Peoples (Convention of Biological Diversity, 2013). Expectedly, the presence of Indigenous Peoples and Local Communities (IPLC) across forests influences the distribution of carbon stocks. For example, Indigenous Lands and Protected Areas, some of which are inhabited by Local Communities, and their overlaps store more than half of the carbon stocks in the Amazon Basin (Walker et al., 2020). This estimate suggests that the potential of Natural Climate Solutions in the neotropics largely depends on IPLC.

IPLC in forest lands, including those in the neotropics, display distinctive worldviews, knowledges, and values regarding nature. Compared with Eurocentric worldviews that understand nature by considering knowledge and knower as separate entities, indigenous worldviews consider both as interconnected, and thus, indigenous knowledges are better understood as ways of living (Aikenhead & Ogawa, 2007). For that reason, indigenous knowledges have been defined as knowledge-practice-belief complexes about peoples-nature interactions (Berkes, F., Colding, J., & Folke, 2000) that have evolved from adaptive processes, and have been culturally transmitted through generations (Berkes et al., 1995). The action-oriented character of indigenous worldviews manifests itself in relational values among people and between people and nature that articulate through informal institutions. This articulation results in ecosystem management practices such as monitoring species abundances, protecting vulnerable species' life stages, temporarily restricting harvest, or completely forbidding access to particular habitats and species (Berkes, 2008). Local Communities, which have evolved from historical voluntary or involuntary displacements and exchanges between different social groups, share multiple aspects of Indigenous Peoples' worldviews about nature, such as accumulated knowledge, adaptive innovations, and similar ecosystem management practices aiming for sustainability (Convention of Biological Diversity, 2013). Furthermore, IPLC relational values with nature manifest in place-based symbolic meanings, social cohesion, identity, and other cultural expressions (Pascua et al., 2017; Winthrop, 2014).

IPLC relational values have actively transformed forest ecosystems. A common feature of IPLC forests is the land management meant to secure food production along with other instrumental values, such as household materials and game that are fundamental for local livelihoods (FAO, 2022) and income (Angelsen et al., 2014). Usually, IPLC management practices result in different coexisting areas under varying levels of intervention and biodiversity (Schroth, Harvey, et al., 2004). For example, forest landscapes managed by Indigenous Peoples are the sum of swidden agriculture fields, fallows and secondary forests sometimes enriched with particular species, and old-growth forests that create ecological gradients (Toledo et al., 2003). In other cases, Local Communities have made agroforests of planted rubber trees along riverbanks (Schroth, Moraes, et al., 2004). These forms of traditional landscape management and engineering seem to explain species abundances and assemblages across whole biomes like the Amazon Basin (Levis et al., 2017). Due to this active landscape management that spans from decades to millennia, Michon et al. (2007) defined IPLC forested lands as domestic forests.

Regardless of the levels of human intervention, domestic forests are also of ecological value at multiple scales. Indigenous Lands maintain approximately 40% of the intact forest Lands in the neotropics (Fa et al., 2020), which in addition to regulating climate and hydrological regimes, harbor native biological diversity and viable populations of wide-range species (Potapov et al., 2017). Other domestic forests with higher levels of human intervention are of ecological value as well. For example, shifting cultivation systems (Pelletier et al., 2012) and orchards (Wood et al., 2016) have been found to maintain considerable carbon stocks, potentially retaining other key ecological functions. Whereas these land uses may contain fewer species at the local scale compared to old-growth forests, they favor ecological succession and biodiversity at the landscape scale (Chazdon et al., 2009). Thereby, the domestic forests managed by

IPLC are not necessarily pristine landscapes but have the potential to maintain ecological integrity and provide a diverse range of values that include climate change mitigation, biodiversity conservation, and local livelihoods.

As with other tropical forests, IPLC domestic forests and their values have been the subject of different policy interventions. Following Borner et al. (2020), these policy interventions can be classified as enabling, disincentives, and incentives. Enabling interventions aim to benefit particular stakeholders with one or several values regarding nature (Börner & Vosti, 2013). Although IPLC domestic forests represent a customary form of land tenure, granting land tenure rights represents an enabling intervention that protects land ownership, guarantees access to instrumental and relational values regarding nature, and excludes other stakeholders (Gray et al., 2015). Other interventions can be considered disincentives because they aim to discourage stakeholders from accessing lands to guarantee particular values regarding nature (Börner & Vosti, 2013). Strict Protected Areas are typical disincentives that limit most human activities to conserve biodiversity (Dudley et al., 2010). Domestic forests have been a common target of PAs, resulting in different levels of restricted access and management for IPLC (Borrini-Feyerabend et al., 2004). Lower restriction levels usually come in the form of enabling interventions that decentralize Protected Areas' governance, such as forest concessions or allowing sustainable use (Agrawal et al., 2008).

Conversely, the incentives aim to reward stakeholders under the condition of achieving certain goals related to specific values regarding nature. That is the case of REDD+, which was designed to provide result-based payments on reduced land-use emissions to mitigate the effects of climate change (Maniatis et al., 2019). In practice, the rewards from REDD+ to IPLC vary: local REDD+ projects provide direct result-based payments against some baseline or business-as-usual scenario (Hodgdon et al., 2013; Sills et al., 2014), and national and subnational REDD+ find different criteria (e.g., conserving forest) to provide financial benefits (de Koning et al., 2011; Rosa Da Conceição &

Börner, 2020). In summary, a complex array of external policy interventions has inevitably influenced IPLC's forest management.

Given domestic forests' potential contribution to climate change mitigation, biodiversity conservation, and other values regarding nature, understanding the interplay between IPLC's worldviews, values, and landscape management with external policy interventions is of the utmost importance. To this end, this thesis aims to answer the question: how do IPLC's land tenure, external policy incentives, and local values influence forest cover and carbon stocks stability in the neotropics? The first and second chapters rely on remote sensing and quasi-experimental methods to estimate IPLC domestic forests' effect on climate change mitigation and forest conservation after removing biases in their location. Concretely, the first chapter aims to estimate the temporal and spatial effects of Indigenous Lands, their overlaps with Protected Areas, and non-overlapping Protected Areas on aboveground carbon stocks in Panama and the Amazon Basin portions of Ecuador, Peru, Colombia, and Brazil. The second chapter explores the diversity of governance systems in Protected Areas, particularly those managed by Local Communities (hereafter, Community Managed PAs), and assesses their effectiveness on forest carbon dynamics before and after the adoption of REDD+ programs in Petén (Guatemala) and Acre (Brazil). Based on the results from these chapters, the third explores the potential values linked to land use and forest cover stability in IPLC domestic forests. Using remote sensing and participatory mapping, the third chapter analyzed the spatial patterns of deforestation, disturbance, and values regarding nature in IP Lands from Eastern Panama. The final discussion highlights the general patterns of IPLC management in the domestic forests from the neotropics and the implications in climate change mitigation, forest conservation, landscape resilience, and policy interventions.

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Chapter 1: Are indigenous territories effective Natural Climate Solutions? A neotropical analysis using matching methods and geographic discontinuity designs.

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Abstract

Indigenous Territories (ITs) with less centralized forest governance than Protected Areas (PAs) may represent cost-effective Natural Climate Solutions to meet the Paris agreement. However, the literature has been limited to examining the effect of ITs on deforestation, despite the influence of anthropogenic degradation. Thus, little is known about the temporal and spatial effect of allocating ITs on carbon stocks dynamics that account for losses from deforestation and degradation. Using Amazon Basin countries and Panama, this study aims to estimate the temporal and spatial effects of ITs and PAs on carbon stocks. To estimate the temporal effects, we use annual carbon density maps, matching analysis, and linear mixed models. Furthermore, we explore the spatial heterogeneity of these estimates through geographic discontinuity designs, allowing us to assess the spatial effect of ITs and PAs boundaries on carbon stocks. The temporal effects highlight that allocating ITs preserves carbon stocks and buffer losses as well as allocating PAs in Panama and Amazon Basin countries. The geographic discontinuity designs reveal that ITs' boundaries secure more extensive carbon stocks than their surroundings, and this difference tends to increase towards the least accessible areas, suggesting that indigenous land use in neotropical forests may have a temporally and spatially stable impact on carbon stocks. Our findings imply that ITs in neotropical

forests support Nationally Determined Contributions (NDCs) under the Paris Agreement. Thus, Indigenous peoples must become recipients of countries' results-based payments.

Introduction

Avoided forest conversion and natural forest management are among the most cost-effective Natural Climate Solutions to meet the Paris Agreement (Griscom et al., 2017). Protected Areas (PAs), cornerstones of biodiversity conservation, may contribute to these cost-effective solutions by preventing carbon stocks losses (MacKinnon et al., 2011). However, since 1990, South America and Central America have tripled the area of PAs (Morales-Hidalgo et al., 2015) while simultaneously losing 10% and 25% of forest cover, respectively (Keenan et al., 2015). These forest conversion trends stress the need for additional Natural Climate Solutions that could reinforce the role of PAs. In Neotropical countries and across the globe, Indigenous Territories (ITs) cover significant portions of natural lands with minimal human disturbance and tend to overlap with PAs (Garnett et al., 2018). More than 30% of the Amazon Basin forest's aboveground carbon stocks are in ITs, and nearly 7% of these stocks are in areas overlapping with PAs (Overlapped Areas, hereafter OAs) (Walker et al., 2020). Thus, ITs and OAs with less centralized governance and providing livelihoods may conserve forests and potentially represent effective Natural Climate Solutions.

However, the effect of ITs, OAs and PAs in forest conservation might be overestimated. These land tenures tend to be located in higher elevations, steeper slopes, and greater distances to roads and cities than unprotected lands, lowering deforestation probabilities (Joppa & Pfaff, 2009, 2010). To control for this non-random spatial location, an increasing number of studies have relied on a statistical technique called matching analysis (Andam et al., 2008; Nelson & Chomitz, 2011). In these studies, matching analysis samples observations with similar geographical characteristics, removing heterogeneous observations, and allowing to compare ITs, OAs, and PAs with unprotected lands. For example, using matching analysis, ITs in the Brazilian Amazon have been found to restrain high deforestation pressure more effectively than PAs (Nolte et al., 2013). Panama's PAs and untitled ITs more effectively avoided deforestation than unprotected lands with similar topography and accessibility (Vergara-Asenjo & Potvin, 2014). Matching analysis also allowed identifying decreased deforestation where ITs and other land tenures overlap (e.g., PAs) in Peru (Anderson et al., 2018). Furthermore, Blackman & Veit (Blackman & Veit, 2018) concluded that ITs in the Amazon Basin of Colombia, Bolivia and Brazil avoid carbon emissions from deforestation. Therefore, controlling for spatial location using matching supports the claim that ITs are as effective as PAs to avoid deforestation.

Despite the influence of anthropogenic degradation and recovery on forest conservation and carbon stocks dynamics, research on matching analysis has been limited to examining the effect of land tenures on avoided deforestation. Shifting cultivation, considered a driver of degradation (Mertz et al., 2012), is common among tropical forest landholders (van Vliet et al., 2012). After long fallow periods (>20 years), shifting cultivation can only recover around 50% of mature forests' carbon stocks (Bruun et al., 2009). Logging and fires, other causes of degradation in tropical forests, remove 45% and 22% of forest's carbon stocks and take decades to recover (Andrade et al., 2017). Thus, accounting for forest degradation and recovery in temporal carbon stocks dynamics may shed a different light on the effectiveness of land tenures in forest conservation, particularly in those with fewer use restrictions (e.g., ITs and OAs). However, little is known about the temporal effect of ITs, OAs, and PAs on carbon stocks dynamics after controlling for spatial location.

Matching analysis controls for spatial location, but it does not guarantee unambiguous estimates of land tenure effects in forest conservation. Karsenty et al. (2017) highlight that matching analysis implies weighting influence to particular deforestation (or degradation) covariates, such as roads or rivers. The choice and omission of covariates influence the observations sampled by matching, potentially excluding relevant areas, and altering the effect attributed to a particular land tenure (Karsenty et al., 2017). In this regard, some have recognized that sampling through matching analysis might not be independent and exclude observations around the boundaries of protected lands (Bowker et al., 2017; Gaveau et al., 2013; Zhao et al., 2019), rather than exploring the implications of sampling across these boundaries. Conversely, the effect of ITs and PAs boundaries on deforestation has been estimated through regression discontinuity designs. Bonilla-Mejía & Higuera-Mendieta (Bonilla-Mejía & Higuera-Mendieta, 2019) found that ITs' boundaries are more effective than PAs at curbing deforestation in Colombia. Similarly, Baragwanath & Bayi (Baragwanath & Bayi, 2020) established that ITs' boundaries with granted property rights in Brazil decrease deforestation. However, few studies have used matching analysis in geographic discontinuity designs, control for geographic distance among observations (Keele et al., 2015), and estimate the effect of ITs and PAs boundaries on carbon stocks. Nor have they addressed whether land tenures with different forest governance, such as ITs and PAs, imply different spatial effects on carbon stocks.

This study builds upon previous research assessing the effect of land tenures on deforestation through matching analysis and addresses some limitations of this methodology. Using Panama and Amazon Basin Countries, this study aims to estimate ITs, OAs, and PAs temporal and spatial effects on aboveground carbon stocks. The hypothesis is that PAs with centralized governance and disincentives on forest use will secure higher carbon stocks than ITs and OAs over time and throughout their boundaries by reducing the influence of anthropogenic degradation. Regardless of forest use disincentives and governance, we find that PAs, OAs, and ITs preserve carbon stocks and buffer losses temporally and spatially across neotropical forests.

Our study makes three contributions to the literature. First, we provide a consistent use of matching analysis in multiple land tenures and countries, allowing us to compare the effects of ITs, OAs, and PAs across neotropical forests. Conversely, previous studies have analyzed either multiple land tenures on a country scale (Blackman, 2015; Pfaff et al., 2014; Vergara-Asenjo & Potvin, 2014) or single land tenure categories across regions (Blackman & Veit, 2018; Nelson & Chomitz, 2011). Second, we use the temporal dynamics of aboveground carbon stocks (2003 to 2016) instead of forest cover, thus making it possible to estimate a more accurate temporal effect of ITs, OAs, and PAs in climate change mitigation. Furthermore, we explore the spatial heterogeneity of these effects through geographic discontinuity designs, allowing us to assess the spatial effect of ITs, OAs, and PAs boundaries on carbon stocks. To our knowledge, this study is among the first to estimate the effect of multiple land tenures on carbon stocks temporally (14 years) and spatially (throughout boundaries), providing a quantified estimate of forest conservation and climate change mitigation across Neotropical Forests.

Theory of change

Our study assumes a causal relationship between ITs, OAs and PAs, the treatments, and forest's carbon stocks, the outcome. Here, we explain the different components and assumptions for this causal relation to occur (Fig 1). Spatial location covariates influencing the suitability of agriculture (e.g., altitude and slope) and market pressure (human settlements, roads, rivers) (Ferretti-Gallon & Busch, 2014; Geist & Lambin, 2002) represent input components driving carbon stocks losses in the treatments and controls (other lands). ITs, OAs, and PAs are known to experience an overall reduced influence from these covariates compared with other lands (Joppa & Pfaff, 2009). Moreover, as market pressure declines inside the treatments boundaries (Barber et al., 2014), forest cover increases (Joppa et al., 2008). Beyond the influence from these covariates, we expect ITs, OAs, and PAs to directly cause positive outcomes, that is, securing larger carbon stocks than other lands (the control). However, these land tenures, are subject to external and indigenous governance (Blackman & Veit, 2018; Börner et al., 2020) that may result in different outcomes.

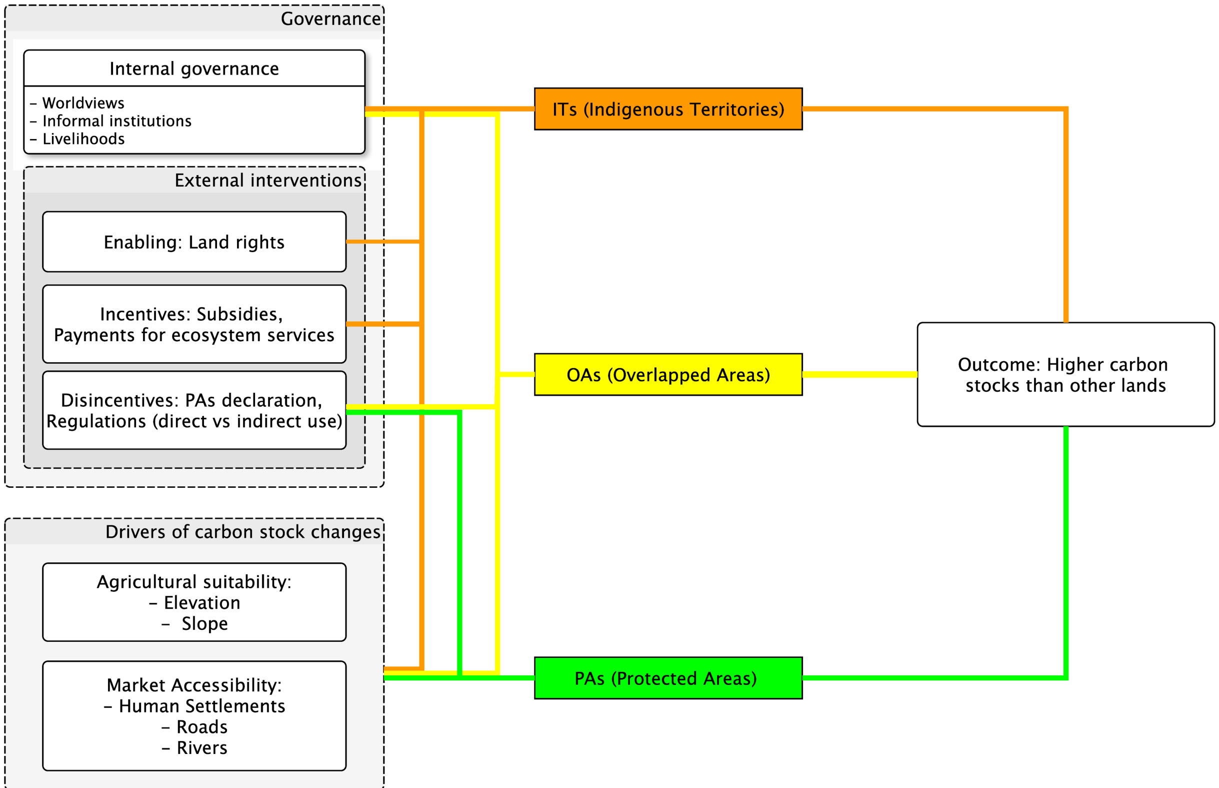

Fig 1. A generic theory of change for land tenures effects on carbon stocks. The lines symbolize hypothetical pathways of how governance components and drivers of carbon stocks change influence ITs (orange), OAs (yellow), PAs (green) to result in an expected outcome.

ITs may result in positive outcomes due to indigenous and external governance. Indigenous governance emerges from worldviews and cultural values that do not privilege ecosystem conservation at the expense of local livelihoods or vice-versa (Villalba, 2013; Walsh, 2010). These forms of governance build informal institutions that restrict access to other agents and limit the spatial and temporal extent of agriculture and other livelihood activities (Berkes et al., 2000). Thus, even if deforestation and degradation caused by permanent and shifting agriculture, logging, and firewood extraction reduce forests' carbon stocks (Hosonuma et al., 2012), their negative effect is expected to be temporally and spatially limited in ITs compared with other lands. Furthermore, external governance interventions may limit the influence of local livelihoods on forests (Börner & Vosti, 2013). For example, governments' recognition of land rights (Chhatre & Agrawal, 2009) or incentives that reward communities for forest conservation actions may contribute to secure carbon stocks (de Koning et al., 2011; Sills et al., 2014).

Regarding PAs and OAs, we assume a predominant influence of external governance. The declaration of PAs (in public or private lands) represents government disincentives to restrict land use, conserve forests (Börner et al., 2020), and consequently limit carbon stock losses temporally and spatially. While certain government regulations may allow direct uses to some agents, PAs tend to have centralized forest governance (UNEP-WCMC et al., 2018). OAs are PAs established in ITs and have been interpreted as external interventions that privilege conservation and limit indigenous governance and livelihoods (Borrini-Feyerabend et al., 2004). Consequently, OAs represent an intermediate treatment between ITs and PAs that also result in limited carbon stock losses compared with other lands. Given that PAs constitute the highest limitation on forest livelihoods, and therefore deforestation, and degradation, we expect that they will result in more substantial effects on carbon stocks than OAs and ITs.

Methods

Geographic scope

The ideas developed in this study emerged from discussions during the annual meeting of the "Red Amazónica de Información Socioambiental Georeferenciada" RAISG (Amazon Georeferenced Socio-Environmental Information Network) carried out in Quito (Ecuador) in August 2018. The authors belong to diverse organizations that participate or collaborate with RAISG. Additionally, some of the authors have collaborated with the "Coordinadora de las Organizaciones Indígenas de la Cuenca Amazónica" - COICA (Coordinator of Indigenous Organizations of the Amazon River Basin), which also participates in RAISG, and the "Alianza Mesoamericana de Pueblos y Bosques" - AMPB (Mesoamerican Alliance of Peoples and Forests). Regarding this study, these collaborations have resulted in sharing and curating geospatial information on PAs and ITs that define our study's geographical scope: Panama and the Amazon Basin portions from Colombia, Ecuador, Peru, and Brazil. Only the authors participated in the research design and the interpretation of the results.

Our study focuses on three land tenures in Panama and Amazon Basin Countries (Fig 2): PAs, ITs, and OAs. PAs encompass national and subnational jurisdictions with governance by governments, private governance, and shared governance that allow sustainable use from privates and communities (Table 1). ITs without official titles or in the process of official recognition (i.e., untitled lands) were also included, except in Colombia, where the data was not available. All ITs overlapping with PAs were defined as OAs. All private and public lands outside ITs, OAs and PAs were defined as other lands.

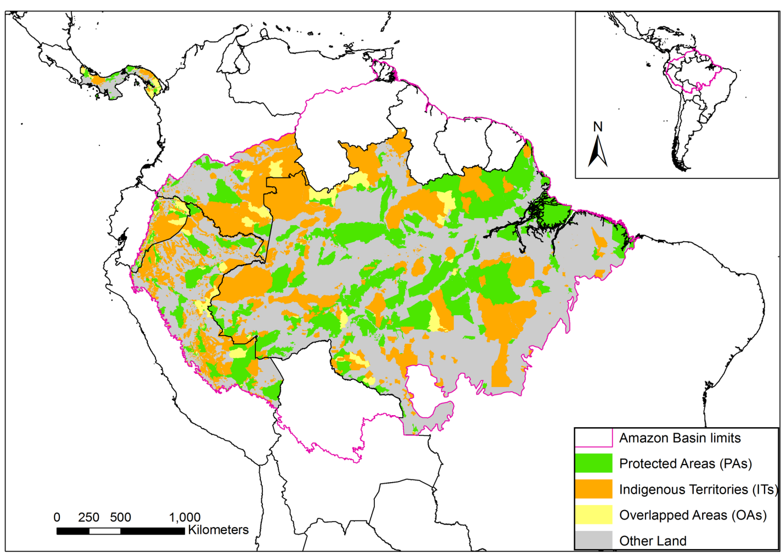

Fig 2. Study Area. Panama and the Amazon Basin portions of Colombia, Ecuador, Peru, and Brazil. Land tenure is classified as PAs (green), ITs (orange), OAs (yellow), and Other Land (grey).

Table 1. PAs and ITs included in the study.

Country	Protected Areas (PAs)	PAs IUCN Category	Indigenous Territories (ITs)
Panama	National Park	II	Titled: "Comarcas"
	Protective Forest	V	Titled: Collective Territories
	Wildlife Refugee	IV	Claimed/Untitled
	Multiple Use Area	VI	
	Forest Reserve	IV	
	Hydrological Reserve	V	
	Zone of hydrological protection	V	
Colombia	National Park	I-II	Titled: Indigenous Reserve
	National Protective Forest Reserve	VI	
	National Forest Reserve	I	
	Civil Society Nature Reserve	VI	
	Fauna and Flora Sanctuary	IV	
Ecuador	National Park	NR*	Titled
	Protective Forests	NR	Declared
	Ecological Conservation Area	NR*	Claimed/Untitled
	Biological Reserve	NR*	
	Ecological Reserve	NR*	
	Fauna Production Reserve	NR	
	Wildlife Refugees	NR	
Peru	National Park	NR*	Titled / Declared: Native community

	National Sanctuary	NR*	Titled/ Declared: Peasant community
	Historical Sanctuary	NR*	Claimed/Untitled
	Protective Forest	NR	
	Landscape Reserve	NR	
	Communal Reserve	NR	
	Hunting Reserve	NR	
Brazil	National Park	II - NR*	Titled/ Declared: Indigenous Area
	Environmental Protection Area	NR	Titled/ Declared: Native Community
	Area of Relevant Ecological Interest	NR	Titled / Declared: Indigenous Reserve
	Ecological Station	NR*	Titled / Declared: Indigenous Territory
	Natural Monument	III	Claimed/Untitled
	Nature Reserve	NR*	
	Biological Reserve	NR*	
	Sustainable Use Reserve	NR	
	Ecological Reserve	NR*	
	Extractive Reserve	NR	
	State Forest	NR*	
	State Park	NR*	
	Wildlife Refugee	NR*	

PAs are accompanied by IUCN categories, except when not reported (NR) and only allowing indirect use*. ITs overlapping with PAs are considered OAs.

Spatial data and processing

The boundaries of ITs and PAs were curated by the Neotropical Ecology Laboratory (McGill University, Smithsonian Tropical Research Institute) for Panama; and RAISG

(Amazon Geo-referenced Socio-Environmental Information Network) in the case of Amazon Basin Countries. This spatial information was used to determine the overlaps of ITs and PAs, here defined as OAs.

We used Annual carbon density maps based on raster data (~500 m resolution) that was generated by the Woodwell Climate Research Centre between 2003 and 2016 and explained in detail by Baccini et al. (Baccini et al., 2012, 2017) and Walker et al. (Walker et al., 2020). These estimations derive from combining LiDAR data and field measurements that calibrate a machine learning algorithm that generates annual carbon density estimates from MODIS satellite imagery. These carbon density maps can detect annual losses and gains in carbon density, aggregating changes from deforestation, forest degradation, and recovery.

Elevation, slope and the distance to roads, settlements and rivers were included as covariates to establish the spatial location conditions associated with annual carbon density across countries (Table A in S1 Appendix). Elevation and slope were obtained from the satellite imagery of the SRTM (Shuttle Radar Topographic Mission - Arc Second Global). The distance to roads was calculated from geospatial data produced by national institutions in Panama. Road distance corresponding to Amazon Basin countries was based on the geospatial data curated by RAISG. The distances to rivers and settlements (> 5000 people) were calculated from geospatial data produced by national institutions. Land tenure and covariate data were resampled to the spatial resolution of carbon density, creating observation units of ~500-m resolution across different land tenures with estimates for covariates and carbon density. All geoprocessing was performed in ArcGIS (ESRI, 2018). Finally, we established the non-random spatial location of ITs, OAs, and PAs by estimating their mean covariate differences with other lands in each study area using Mann Whitney tests (Table B in S1 Appendix).

Temporal effects on carbon stocks

As an initial analysis, we performed matching analysis and linear mixed models to control for spatial location and infer the temporal effect of ITs, OAs, and PAs on carbon stocks relative to other lands (Fig 3). Matching analysis preprocesses datasets to reduce the association of a treatment variable with covariates by removing heterogeneous observations and creating a subset of treatment and control observation units with similar covariate values (Diamond & Sekhon, 2012). Here, the treatment variable corresponded to land tenure, and matching created subsets of observation units of ~500 m resolution in the treatment (i.e., ITs, OAs, and PAs) and control (i.e., other lands) with similar slope, elevation, and distance to roads, settlements, and rivers. To account for the size and heterogeneity of the Brazilian Amazon, we included the states as covariates in this country.

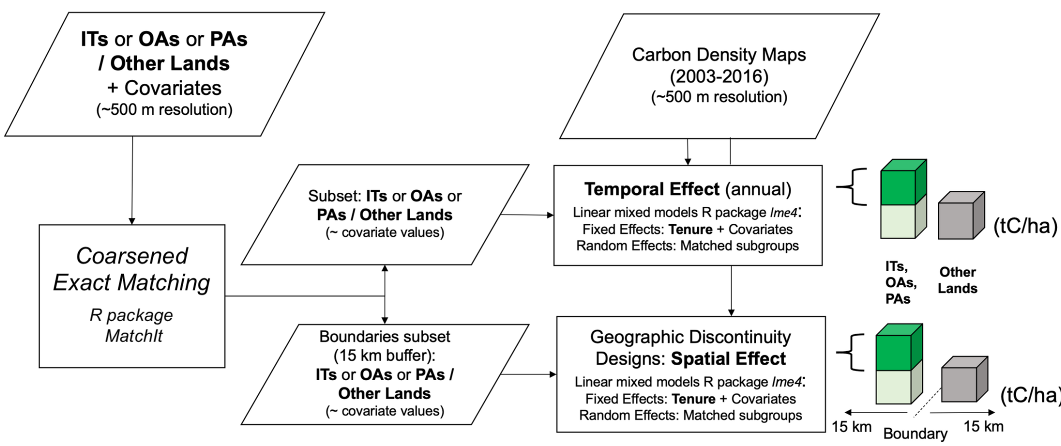

Fig 3. Workflow to infer the temporal and spatial effect of ITs, OAs, and PAs on carbon stocks.

Specifically, we used coarsened exact matching (CEM) (Iacus et al., 2015) with the R package MatchIt (Ho et al., 2015) for ITs, OAs, and PAs in all study areas. Following steps from Iacus et al. (2012), we first defined coarsening choices for each covariate (Table C in S1 Appendix). For example, the elevation was coarsened in multiple categories based on 100 meters intervals. This coarsening choice meant that observation units with elevation values between 900 and 1000 m were considered "equivalent". Then, CEM located control and treatment observation units in matching sub-groups with equivalent coarsened values for all covariates. The third step pruned matching sub-groups that did not have at least one treatment and one control observation with equivalent coarsened covariate values. These steps were reiterative until the coarsening choices produced a covariate balance between treatments and controls. The covariate balance before and after matching was assessed through standardized mean differences and Kolmogorov-Smirnov statistics (Stuart, 2010) (Figs A and B in S2 Appendix). The balance assessments were performed in the R package Cobalt (Greifer, 2021).

After isolating the effect of spatial location through matching, we made temporal estimates regarding the effect of allocating ITs, OAs, and PAs on carbon stocks in each country. This effect was calculated using linear mixed models in the R package lme4 (Bates et al., 2019) with the general expression defined as:

$$y_t = b_{0t} + b_{1t}x_t + \beta Z_t + \alpha + e_t \quad \textbf{(1)}$$

where y_t was carbon density in year t, the outcome variable, and b_{0t} was the fixed intercept. b_{1t} and x_t were the fixed effect slope and predictor of land tenure (i.e., dummy for ITs, OAs, and PAs), respectively. Additionally, β was a vector of additional fixed effects for a vector of predictors Z_t, containing the covariates elevation, slope, and distance to roads, settlements, and rivers. Including the covariates as fixed effects span any remaining imbalances from the matched subsets. The matched sub-group (matched observation units in treatments and control with similar covariate values) was the random effect α_t to account for the structure of the matched subsets. These linear mixed models were estimated annually between 2003 and 2016 in all ITs, OAs, and PAs and study areas. Two parameters derived from the linear mixed models were used to determine the effect of ITs, OAs, and PAs on carbon stocks after controlling for spatial location: the fixed effects intercept b_{ot} and fixed effects slope b_{1t}. b_{ot} refers to the average annual carbon density found in other lands lacking a protected status and represents the carbon stocks baseline for ITs, OAs, and PAs. b_{1t} refers to the annual average differences of carbon stocks between these land tenures and other lands, defined as the temporal effect.

Spatial effects on carbon stocks

After calculating the distance of matched observation units around the boundaries of ITs, OAs, and PAs, we used geographic discontinuity designs to examine the spatial heterogeneity of the temporal effects. Geographic discontinuity designs estimate the effect of administrative boundaries (Keele & Titiunik, 2015), here defined as spatial effects. Specifically, we assessed how ITs, OAs, and PAs boundaries influence carbon stocks compared with other neighbouring lands. Our geographic discontinuity designs are based on two assumptions. First, following Keele et al. (Keele et al., 2015), we assume that after controlling for covariates and the geographic distance (i.e., the distance among observations throughout a boundary), the treatment assignment occurs as-if randomized, allowing to estimate the spatial effects. Our second assumption, which derives from the first, is that the spatial effect is a function of the treatment of interest (Keele & Titiunik, 2015). This assumption implies that the boundaries of ITs, OAs, and PAs will influence carbon stocks.

To implement the geographic discontinuity designs, we created subsets of observation units with buffer zones inside and outside of ITs, OAs, and PAs boundaries of 0-0.5 km, 0–1 km, 0–5 km, 0-10 km, and 0–15 km. We chose these buffer zones because covariates' pressure usually ceases between 5 and 10 km (Barber et al., 2014), and the vegetation seems to stabilize in PAs and ITs around 15 km (Joppa et al., 2008). Similar to Keele et al. (Keele et al., 2015), we used matching methods to find treatment and control observation units with similar covariates. As the temporal effects matching, we performed CEM within the buffer zones subsets, including slope, elevation, and distance to roads, settlements, and rivers as covariates. Additionally, we controlled for the geographic distance among observation units according to buffer zones. For example, in buffer zones 0–1 km, we included matches across a 2-km radius, and in 0–

15-km buffer zones, a 30-km radius. The covariate balance before and after matching was assessed through standardized mean differences and Kolmogorov-Smirnov statistics (Figs C and D in S2 Appendix).

The differences between average carbon stocks stored inside and outside the boundaries of ITs, OAs, and PAs, or the spatial effects, were also estimated through the linear mixed models aforementioned in 2003 and 2016. The covariates were included as fixed effects, spanning any remaining imbalances from matching. To support the credibility of the spatial effects, we performed falsification tests where each covariate in Z_t was treated as an outcome variable y_t according to the linear mixed model above (Keele & Titiunik, 2015). The falsification tests showed that allocating ITs, OAs, and PAs had negligible effects on the covariates after matching (Fig E in S2 Appendix). The annual spatial effects, covariate balance tests, and falsification tests were estimated in all ITs, OAs, and PAs, across multiple buffer zones (0-1 to 0-15 km) and study areas.

The geographic discontinuity designs support the previous assumptions. Matching guarantees that observations inside and outside ITs, OAs, and PAs will be valid counterfactuals as they share distance to the boundaries (e.g., 0-1 km), mutual proximity (e.g., 2 km radius), and covariates influence. This role of matching is confirmed by the covariate balance tests and the falsification tests. Thus, the treatments assignment (i.e., ITs, OAs, and PAs) occur as-if randomized (first assumption). Moreover, we account for local effects by matching valid counterfactuals in neighboring subgroups and incorporating them as random effects in the linear mixed models. These local effects might control the influence of unobserved covariates that operate on a local or restricted geographical scale, ensuring that the overall spatial effect is a function of the treatments (second assumption). Finally, if the assumption of valid counterfactuals holds across multiple buffer distances to treatments boundaries, it is possible to estimate the heterogeneity of the spatial effects. In other words, it is possible to explore how the spatial effects vary at multiple distances from ITs', OAs', and PAs' boundaries.

Sensitivity analysis

Matching is expected to control for observed covariates and correlated unmeasured covariates (Stuart, 2010). In our study, unmeasured covariates that influence carbon stocks include population, opportunity costs from agriculture and cattle, or the probability of fire occurrence. However, these unmeasured covariates are correlated with other covariates of market pressure and agricultural suitability (Angelsen, 2010; Nelson & Chomitz, 2011) (i.e., the observed covariates). Thus, we used sensitivity analyses to assess the effect of unmeasured covariates unrelated to the observed covariates but related to the treatments (i.e., ITs, OAs, and PAs) and their effects (temporal or spatial) (Liu et al., 2013).

Particularly, we estimated the E-value, which represents the minimum strength that an unmeasured covariate would need to have with the treatment and its effect, for the treatment and effect association not to be causal (VanderWeele & Ding, 2017). This value is an estimate that accommodates effects from observational studies (i.e., not randomly assigning the treatment and control) that do not have 1-1 matched pairs (CEM matches multiple observations in subgroups) (Liu et al., 2013). The E-value can be calculated by the expressions:

$$\mathrm{d} = \frac{\mathrm{b_{1t}}}{\sigma} \quad (2)$$

$$\mathrm{ER} = \mathrm{e}^{1.81\mathrm{d}} \quad \mathbf{(3)}$$

$$\mathrm{E-value} = \mathrm{ER} + \sqrt{\mathrm{ER\,(ER - 1)}} \quad \mathbf{(4)}$$

where b_{1t} is the fixed effects slope for land tenure, that is the temporal or spatial effect, σ is the standard deviation of the temporal or spatial effect, d is the standardized temporal or spatial effect, and ER is the effect ratio. ER, equivalent to a Risk Ratio, compares the probability of a positive spatial/temporal effect in ITs, OAs, and PAs with the probability of a positive effect in other lands. The expressions above are further justified in (VanderWeele & Ding, 2017). In our study, an ER greater than 1 indicates a greater probability that ITs or OAs, or PAs will store higher carbon stocks than other lands, either temporally or spatially. For example, an ER of 2 in ITs means that, after controlling for covariates, ITs are two times more likely to store higher carbon stocks than other lands. A hypothetical E-value of 3 would imply that the ER of 2 could be explained away by an unmeasured covariate that was associated with both the allocation of ITs (i.e., treatment) and annual carbon stocks (i.e., outcome) each by 3-fold, above and beyond the observed covariates. However, a weaker unmeasured confounding could not alter the ER and, therefore, the spatial and temporal effects. Following (VanderWeele et al., 2019), the E-value assesses the strength of an unmeasured covariate to alter the temporal and spatial effect of ITs, OAs, and PAs on carbon stocks. This value was estimated with the R package Evalue (Mathur et al., 2021) for all spatial and temporal effects in 2003 and 2016 across the study areas.

Results

The temporal effect of Indigenous Territories and Protected Areas on carbon stocks

Matching analysis and the linear mixed models controlled the influence of spatial location covariates, allowing to estimate the temporal effect of allocating ITs, OAs, and PAs on carbon stocks. This temporal effect represents the annual mean difference of carbon stocks between these land tenures and other lands. Across Panama and Amazon Basin countries, the carbon stocks from 2003 to 2016 in ITs, OAs, and PAs were usually higher than other lands (i.e., the baseline), resulting in positive temporal effects (Fig 4). According to sensitivity analyses, an unmeasured covariate would need to have a stronger effect than ITs, OAs, and PAs through pathways independent of the covariates to modify these temporal effects (Fig A in S3 Appendix).

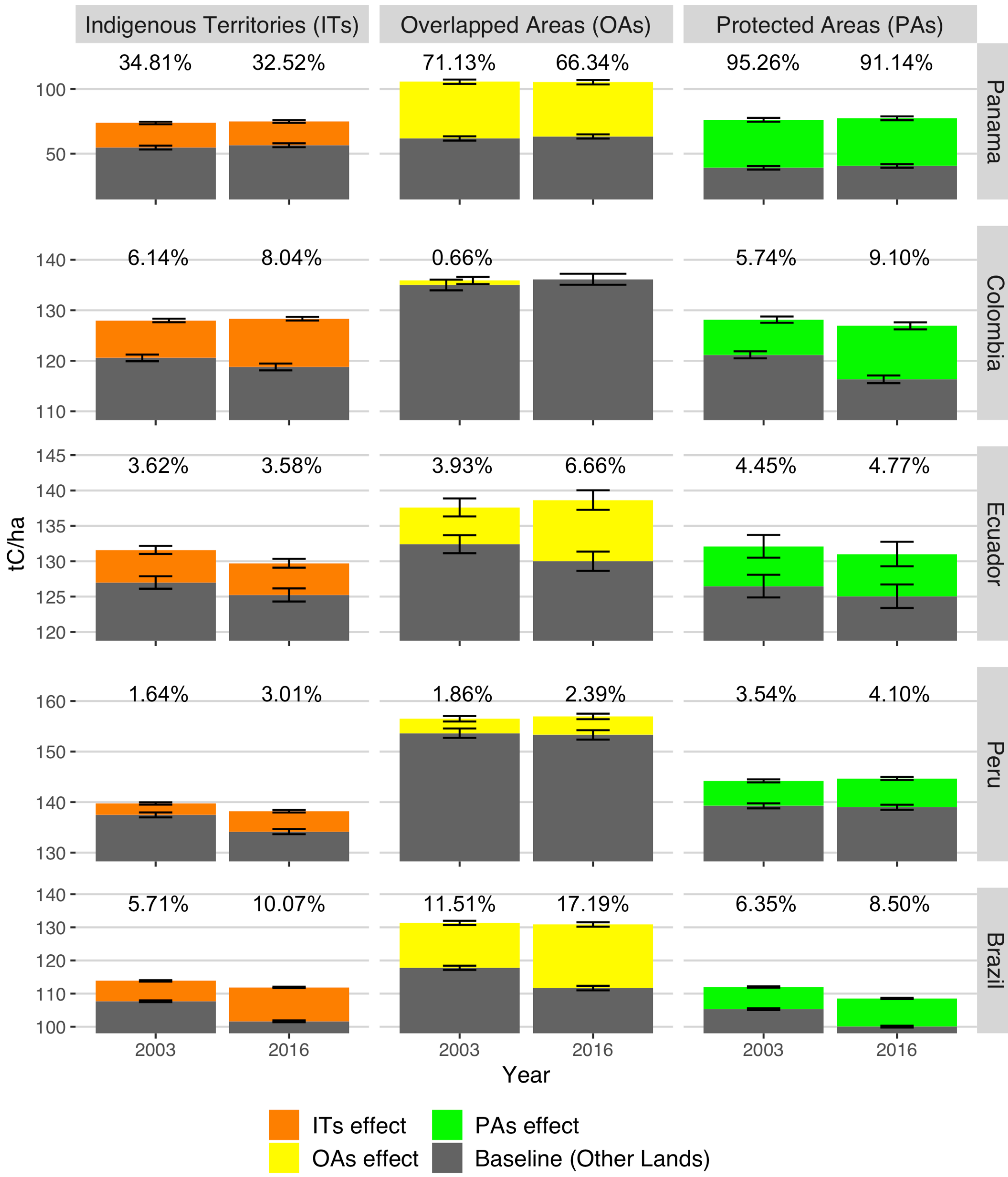

Fig 4. The temporal effects of ITs, OAs and PAs on aboveground carbon stocks across neotropical countries in 2003 and 2016. Significant temporal effects ($p < 0.05$) are represented as colored bars and percentages, indicating the additional/fewer carbon stocks secured by allocating ITs (orange), OAs (yellow), and PAs (green) relative to the baseline (Other Lands, grey) after controlling for spatial location. Error bars reflect 95% confidence intervals for the baselines and temporal effects.

Country-level comparisons of temporal effects in ITs, OAs, and PAs reveal three regional patterns (Fig 4). Panama had low carbon stocks baselines in other lands (< 65 t C/ha) and substantial temporal effects that represented an increase in carbon stocks above 30%. Brazil displayed moderate baselines (< 115 t C/ha) and temporal effects (< 18%). The carbon stocks baselines in western Amazon Basin countries exceeded those of Brazil (> 115 t C/ha), while the temporal effects were moderate (< 10%). Hence, the temporal effects seem substantial in countries with reduced carbon stocks in other lands.

The positive temporal effects also reveal the additional amount of carbon stocks secured by allocating ITs, OAs, and PAs in a particular year compared to other lands (i.e., baseline) across Panama and Amazon Basin countries (Fig 4). During 2003, PAs in Panama secured 95% (37 t C/ha) larger carbon stocks than their baseline (39 t C/ha). Relative to more substantial baselines (> 55 t C/ha), Panama's ITs and OAs accounted for 35% (19 t C/ha) and 71% (44 t C/ha) additional carbon stocks. Similar to Panama, ITs, OAs, and PAs in Amazon Basin countries represented positive temporal effects in 2003. Brazil's ITs and PAs represented 6% (~6 t C/ha, respectively) additional carbon stocks compared to their baselines (~105 t C/ha), and this effect nearly doubled in OAs (12%, 14 t C/ha). Western Amazon Basin countries displayed similar temporal effects in 2003, ranging between 1.6 – 6.1% (i.e., 5 - 7 t C/ha) in ITs from Peru and Colombia, 3.5 – 5.7 % (i.e., 5 - 7 t C/ha) in PAs from the same countries, and 0.7 – 4 % (i.e., 0.5 - 5 t C/ha) in OAs from Colombia and Ecuador. Despite regional differences, these results suggest that in 2003 OAs and ITs had a similar effect on carbon stocks compared to PAs in neotropical countries.

Overall, the temporal effects on carbon stocks remained stable or increased relative to other lands until 2016 (Fig 4 and Fig A in S4 Appendix). These effects remained stable in PAs and ITs from Ecuador and did not vary more than 0.5%. ITs in other Amazon Basin countries exhibited increases in temporal effects, reaching between ~ 3% (4 t C/ha) in Peru and ~10% (10 t C/ha) in Brazil. Similarly, Amazon basin PAs had increases that resulted in temporal effects between ~ 4% (~11 t C/ha) and ~ 9.1% (9.5 t C/ha) for Peru and Colombia, respectively. The temporal effects considerably varied in Amazon Basin OAs during 2016, showing no differences with the baseline in Colombia and the largest increase in Brazil (17.2%, 19 t C/ha). Conversely, ITs, OAs, and PAs in Panama experienced decreases in temporal effects (> -5%) that seem to be driven by the recovery of carbon stocks in other lands (Fig B in S4 Appendix). Thus, stable and increasing temporal effects reflect that allocating ITs, OAs, and PAs buffered losses and secured the stability of carbon stocks relative to the other lands. Furthermore, these results reveal that indigenous lands (i.e., ITs and OAs) and PAs secured similar amounts of carbon stocks until 2016.

Insight at a finer scale: the spatial effect of Indigenous Territories and Protected Areas on carbon stocks

To identify the spatial implications of matching analysis in quantifying forest conservation, we estimated the distance of observation units to the boundaries of ITs, OAs, and PAs (Fig 5, Table 2). Matched observation units in these land tenures had a range of average distances to their boundaries, between 1.3 km (± 2.26) in PAs from Ecuador and 10.15 km (± 11.70) in PAs from Peru. The distance of matched observation units in other lands to ITs', OAs', and PAs' boundaries ranged between 3.10 km (± 3.13) (Ecuador) and 9.52 km (± 7.72) (Panama). Not surprisingly, the spatial distributions imply that observations along these boundaries are more likely to share spatial features (i.e., elevation, slope, and distance to roads, settlements, and rivers). Moreover, most human settlements inside ITs, OAs, and PAs tend to be located in these accessible areas, especially less than 5 km from the boundaries (Fig C in S4 Appendix). In the case of observations in ITs, OAs, and PAs, these sampling outcomes suggest that matching analysis selects the most accessible areas, omitting the core and possibly more intact forests. Thus, the spatial distribution from matching indicates that ITs', OAs', and PAs' temporal effects are conservative.

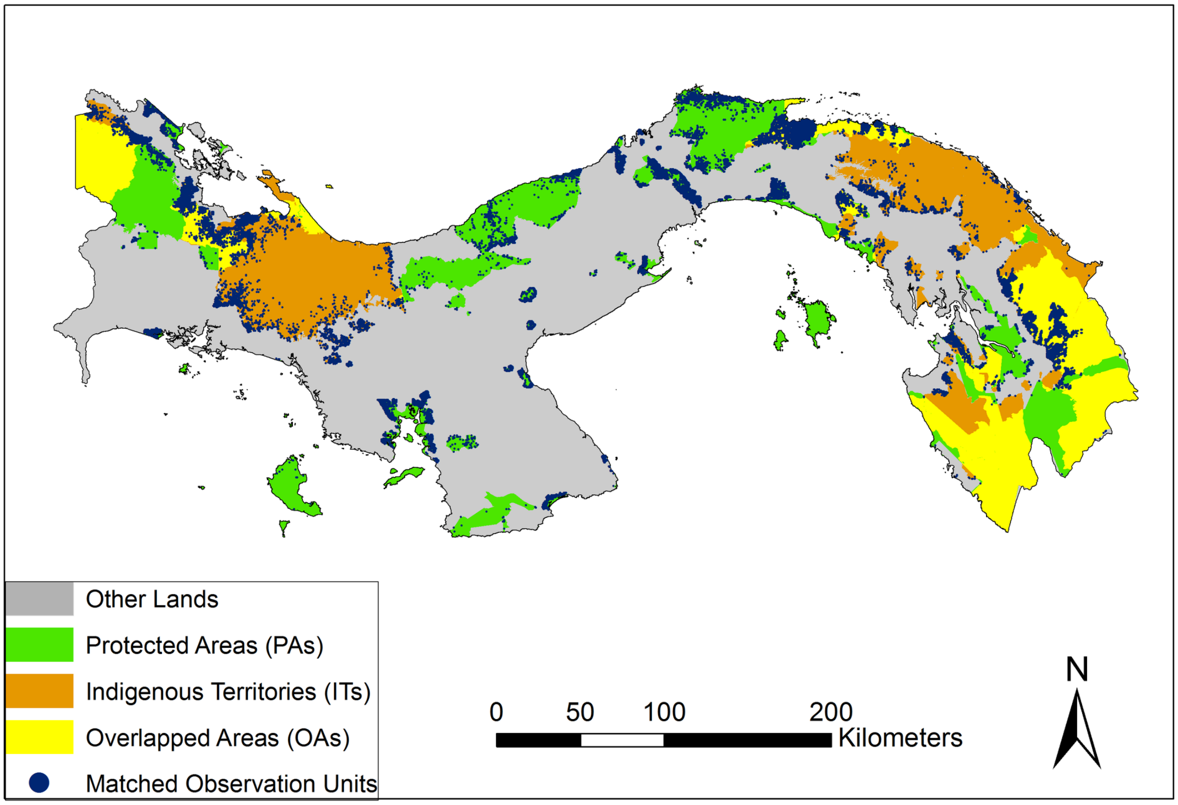

Fig 5. Observation units sampled through matching analysis in ITs, OAs, and PAs from Panama.

Considering the spatial distribution of matched observations, we performed geographic discontinuity designs to understand how carbon stocks varied spatially throughout the boundaries of ITs, OAs, and PAs in 2003 and 2016. The geographic discontinuity designs estimate spatial effects. That is, the mean differences of carbon stocks inside and outside these land tenures for various distances around their boundaries, after controlling for spatial location. Overall, the geographic discontinuity designs show that carbon stocks increase inside the boundaries in 2003 and 2016 (Fig 6). To explain away these effects, an unmeasured covariate would require a stronger effect than ITs, OAs, or PAs, especially as the distance increase from the boundaries, and above and beyond the covariates of spatial location (Fig B in S3 Appendix). As discussed below, the geographic discontinuity designs reveal spatial and spatial-temporal patterns across ITs, OAs, and PAs.

Table 2. Mean distance to ITs', OAs', and PAs' boundaries of observation units sampled through matching analysis by country and land tenure.

Country	Land tenure	Mean distance to boundaries (km)	SD
Panama	Other Lands	9.51	7.72
	PAs	1.04	1.41
	ITs	2.37	2.99
	OAs	2.25	2.75
Colombia	Other Lands	10.57	10.70
	PAs	6.32	5.25
	ITs	9.35	1.34
	OAs	8.69	7.55
Ecuador	Other Lands	3.10	3.13
	PAs	1.30	1.55
	ITs	1.39	2.25
	OAs	1.48	1.80
Peru	Other Lands	6.57	6.72
	PAs	10.15	11.70
	ITs	1.94	3.24
	OAs	6.37	5.62
Brazil	Other Lands	6.19	4.26
	PAs	6.12	4.25
	ITs	6.11	4.25
	OAs	5.86	4.20

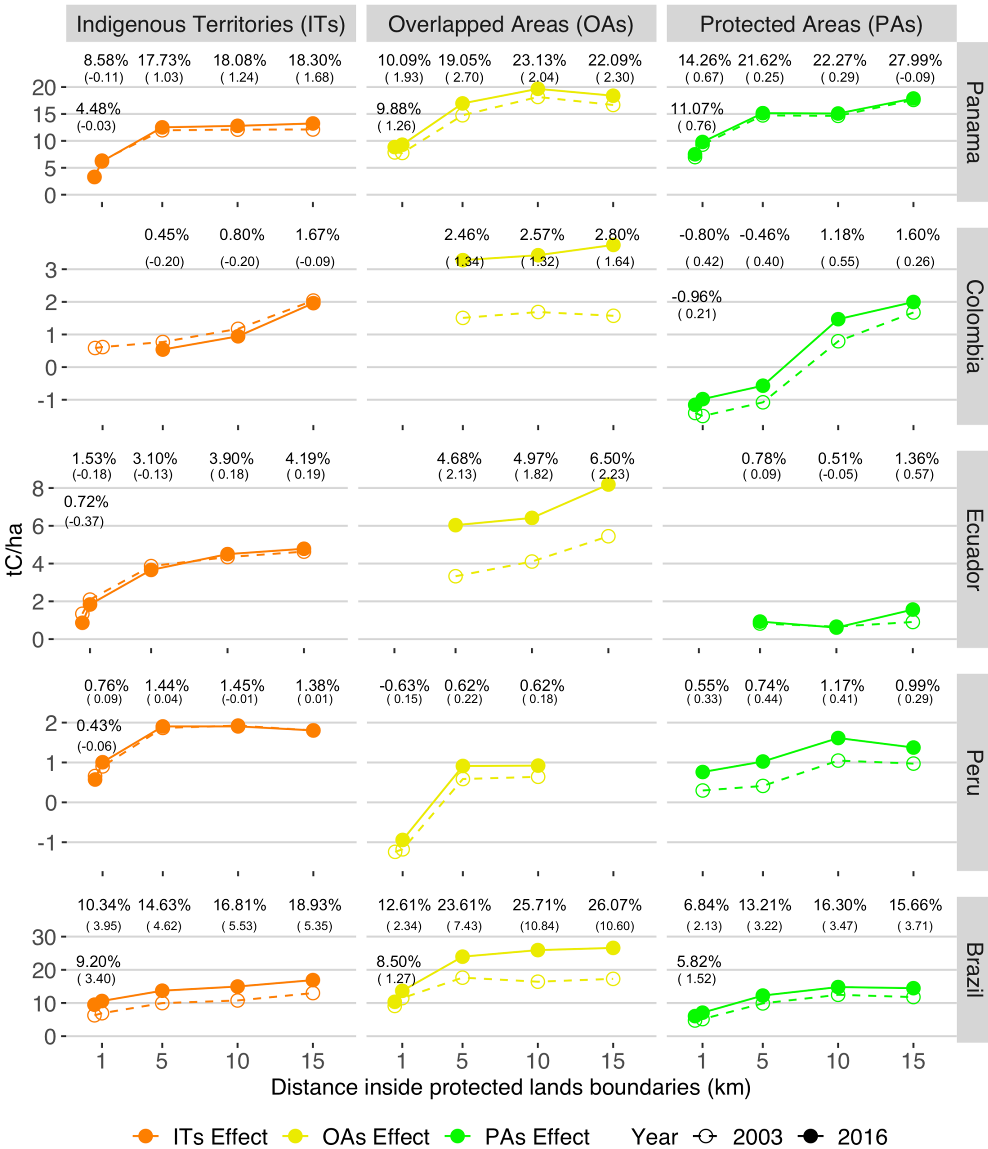

Fig 6. The spatial effect of ITs, OAs', and PAs on carbon stocks during 2003 and 2016 in neotropical countries. Significant temporal effects ($p < 0.05$) are represented as points and percentages, indicating the additional/fewer carbon stocks secured inside the boundaries of ITs (orange), OAs (yellow), and PAs (green) relative to surrounding lands at multiple buffer distances (0-0.5 to 0-15 km). The spatial effects in 2003 are represented by empty points and dashed lines, while in 2016, they are full points and continuous lines. The values in parentheses represent the percentual increase/decrease in spatial effects between 2003 and 2016. Error bars reflect 95% confidence intervals for the temporal effects.

The spatial patterns of geographic discontinuity designs exhibit how ITs, OAs, and PAs influence carbon stocks within their boundaries. We found that the spatial effects of these land tenures tend to increase with the buffer distance to boundaries. At 0.5 km, the spatial effects are minimum or even insignificant; they become pronounced between 1 and 5 km and usually level off at 10km (Fig 6). For instance, ITs from Brazil in 2016 had carbon stocks 10.3% (21 t C/ha) larger than surrounding areas (102 t C/ha) when comparing a 1 km buffer. This spatial effect increased to 15% (27 t C/ha) at 5 km, 17% (~30 t C/ha) at 10 km, and 19% (~34 t C/ha) at 15 km. ITs in Panama and western Amazon Basin countries displayed a similar spatial effect. Except for Peru, OAs also had increasing spatial effects, and their influence on carbon stocks exceeded that of ITs and PAs. For example, OAs' carbon stocks in Colombia did not differ from surrounding areas at 1km (120 t C/ha) in 2016 but had a spatial effect on carbon stocks of 2.5% (~7 t C/ha) at 5 km, which is over five times higher than ITs' and PAs' effect in the same country. The spatial influence of PAs varied across countries. Relative to 10 km buffer comparisons, PAs spatial effects on carbon stocks reduce at 15 km in Brazil and Peru. At 1 and 5 km buffers, Colombia's PAs had 0.80% and 0.46% fewer carbon stocks than surrounding lands, respectively. These resulting spatial patterns imply that allocating ITs and OAs generate boundaries that effectively conserve carbon stocks as PAs. Furthermore, the increasing effects on carbon stocks along with the distance to boundaries, more frequent in ITs and OAs, indicate that these land tenures shape forest landscapes by preserving the core and least accessible areas.

A spatial-temporal comparison of geographic discontinuities between 2003 and 2016 may indicate whether the boundaries of ITs, OAs, and PAs bring stability to carbon stocks. From 2003 to 2016, we found that the differences of carbon stocks inside and outside these land tenures increased, except for ITs in Colombia (Fig 6). Colombia's ITs secured larger carbon stocks within their boundaries at 5 km and 10 km in 2016, but these spatial effects reduced 0.2%, potentially driven by a recovery in surrounding areas (Fig D in S4 Appendix). The most substantial increases in spatial effects occurred among OAs. In Brazil, OAs' spatial effect on carbon stocks increased by 11% (~34 to 53 t C/ha) at 15 km in 2016, while ITs and PAs by 5.4% and 3.7%, respectively. Similarly, Ecuador's OAs increased their spatial effects on carbon stocks by 2.2% at 15km, contrasting national PAs (0.6%) and ITs (0.2%). These increases between 2003 and 2016 in spatial effects suggest carbon stocks losses in surrounding areas that were buffered inside the boundaries of ITs, and PAs, but more prominently, in OAs.

Discussion

In this study, we aim to estimate the temporal and spatial effects of allocating ITs, OAs and PAs, on carbon stocks across Neotropical Forests from Panama and the Amazon Basin. Considering that these land tenures tend to be located in higher elevations, steeper slopes, and greater distances to roads and human settlements than other lands, we control the effect of spatial location. Contrary to our hypothesis, ITs and OAs generally preserve carbon stocks and buffer losses as much as PAs. Over time, these land tenures secure more stable and higher carbon stocks than other lands between 2003 and 2016. Spatially, the geographic discontinuity designs show that carbon stocks increase inside the boundaries of ITs, OAs, and PAs. These temporal and spatial effects were conservative and had varied patterns across land tenures and countries.

The effectiveness of Indigenous Territories in conserving forests and carbon stocks

Our findings highlight the need for a "spatially explicit" understanding of matching analysis regarding land tenure and forest conservation. Other studies have already incorporated "spatially explicit" methodologies. Gaveau et al. (Gaveau et al., 2013), for example, provides the spatial distribution of matched observation units among timber concessions, PAs and oil palm concessions in Kalimantan (Indonesia). Bowker et al. (Bowker et al., 2017) in Africa and Zhao et al. (2019) in China exclude from matching analysis other lands in a 10-km buffer around PAs. These studies attempt to avoid spatial autocorrelation by controlling sampling distance, while Negret et al. (2020) test different post-matching models to control this bias and assess avoided deforestation in PAs from Colombia. Other studies use regression discontinuity designs to isolate some effects of spatial location and test the role of ITs and PAs boundaries (Baragwanath & Bayi, 2020; Bonilla-Mejía & Higuera-Mendieta, 2019). Our study presents an integrated approach. On the one hand, the temporal effect resembles matching methods that are not spatially explicit on sampled observation units (Blackman & Veit, 2018; Nelson & Chomitz, 2011; Pfaff et al., 2014; Vergara-asenjo et al., 2015). After exploring the spatial distribution of matched observation units, our findings point that they are located towards geographic boundaries, causing conservative estimates about ITs, OAs, and PAs. On the other hand, we use geographic discontinuity designs with matching analysis to directly control for spatial location and the geographic distance among observations, generating valid counterfactuals inside and outside these boundaries and maintaining conservative estimates (Keele et al., 2015). Hence, our study makes a novel methodological contribution to research by integrating matching analysis and geographic discontinuity designs to test the effectiveness of ITs', OAs', and PAs' boundaries in conserving carbon stocks across neotropical countries.

Our findings support growing evidence indicating that decentralized forest governance can be effective in forest conservation (Blackman, 2015; Newton et al., 2016; Porter-Bolland et al., 2012; Walker et al., 2020). After controlling for spatial location and relative to other lands, we found that allocating indigenous lands (i.e., ITs and OAs) secured similar or even larger carbon stocks than PAs between 2003 and 2016 in Panama and Amazon Basin countries. These findings are in line with Nolte et al. (Nolte et al., 2013), who showed that indigenous lands are more effective than PAs at curbing deforestation pressure in Brazil. By comparing indigenous lands (ITs and OAs) and PAs, our findings complement Blackman & Veit's (Blackman & Veit, 2018) estimates of avoided emissions from deforestation in ITs from Colombia and Brazil (Blackman & Veit, 2018). However, they did not detect a discernible effect from Ecuador's ITs, while our results estimated a positive effect on carbon stocks. Similarly, our results from Panama, where OAs had the most considerable effect on carbon stocks, partially contrast another study where PAs were the most effective in avoiding deforestation (Vergara-Asenjo & Potvin, 2014). These differences with previous studies might be attributable to our outcome variable (annual carbon stocks) that integrates deforestation, degradation, and recovery. Estimating carbon stock changes offer more accurate estimates regarding the effectiveness of ITs, OAs, and PAs, especially in countries where degradation emissions equal or exceed those from deforestation (e.g., Colombia, Ecuador, and Peru) (Walker et al., 2020). Thus, our results demonstrate that indigenous governance complements centralized forest governance, suggesting that titling ITs and formalizing shared governance in OAs while providing material and cultural benefits to their inhabitants can have a pivotal role in climate change mitigation.

Our geographic discontinuity designs provide conservative estimates regarding ITs', OAs', and PAs' effect on carbon stocks within their boundaries. Although the assessments of PAs' boundaries are common in the literature (Joppa et al., 2008; Spracklen et al., 2015), they do not control for spatial location or compare different other land tenure categories. Our findings indicate that PAs' carbon stocks are larger than surrounding areas, but these spatial effects vary within their boundaries. For example, PAs from Colombia seem only to avoid carbon stock losses 10 km inside their boundaries in 2003 and 2016. In Ecuador, PAs seem to have a stronger effect at 5 km than 10 km from their boundaries. These spatial patterns are not due to recent anthropogenic pressures and confirm the persistent inability of some PAs to reduce forest losses inside their boundaries (Bonilla-Mejía & Higuera-Mendieta, 2019; Clerici et al., 2020; Lui & Coomes, 2016). Furthermore, some anthropogenic pressures are not exclusively external, as our results show that a considerable amount of non-indigenous settlements is located in PAs.

Overall, the geographic discontinuities designs show that ITs and OAs tend to secure larger carbon stocks than their surroundings, and this difference tends to increase towards the least accessible areas. Similar results were found in ITs with granted property rights in Brazil (Baragwanath & Bayi, 2020) and titled IT's in Colombia (Bonilla-Mejía & Higuera-Mendieta, 2019), which gradually decrease deforestation inside their boundaries. These gradual reductions in deforestation and degradation imply that indigenous land use decreases carbon stocks in the most accessible forests, where indigenous settlements tend to be located, and conserves core areas. Other studies have shown on a local scale these spatially limited impacts of indigenous land use, such as shifting agriculture and agroforestry, on carbon stocks (Kirby & Potvin, 2007; Tschakert et al., 2007). Additionally, our results reveal that the spatial effect of ITs and OAs remain temporally stable similar to cases from Mexico and Ecuador (Gray & Bilsborrow, 2020; Puc-Alcocer et al., 2019). As established in the introduction, indigenous governance may explain this spatially and temporally stable land use. Indigenous governance comprises institutions known to limit access based on cultural or social affiliations, and those with guaranteed access may develop and enforce rules that define the temporal and spatial extent of local livelihoods (Berkes, 2008). Other factors, such as limited accessibility due to walking distances and changing river navigability, could also limit land use (Jakovac et al., 2017). Consequently, after controlling for spatial location, our results are among the first to establish that indigenous land use in neotropical forests may have a limited and stable spatial impact on carbon stocks.

National contexts matter

Nonetheless, the current and future effects of allocating ITs, OAs, and PAs on carbon stocks are influenced by national contexts. General geographical trends indicate that these land tenures in Panama and Brazil have wider temporal and spatial effects on carbon stocks than Colombia, Ecuador, and Peru. These geographical differences reflect past trends of extensive forest loss in other lands from Panama (Redo et al., 2012) and Brazil (Fearnside & Fearnside, 2017). Moreover, the increasing differences in carbon stocks among ITs, OAs, and PAs with other lands after controlling for spatial location, highlight a growing pressure on neotropical forests. Consequently, their capacity to preserve or reduce carbon stock losses is likely to change. Between 2000 and 2013, tropical South America lost 7.3% of intact forest lands, mostly caused by the expansion of agriculture (Potapov et al., 2017). PAs in Colombia are witnessing an increase in deforestation around their boundaries after the Peace Agreement with the

Revolutionary Armed Forces (FARC) (Clerici et al., 2020). ITs and PAs in southern Peru are threatened by growing road infrastructure, land invasions, illegal gold mining, and coca production (Gallice et al., 2019). Oil blocks in the Ecuadorian Amazon will expand in cover from 32% to 68%, overlapping with biodiversity hotspots in PAs and ITs (Lessmann et al., 2016). In Brazil, limited law enforcement to prevent forest loss from soy, meat, and timber production in the Amazon Basin converge with recent setbacks in the land tenure security of ITs (Carvalho et al., 2019). Land invasions and deforestation in Panama also pose a threat to ITs (Vergara-Asenjo et al., 2017). In this sense, as deforestation and degradation persist, countries' climate benefits from forests are increasingly dependent on the stability of ITs', OAs', and PAs' carbon stocks. The increasing dependence on stable forests points to the need to protect them through land use planning and resource allocation in institutions at the international, national, and sub-national levels (Busch & Amarjargal, 2020; Funk et al., 2019).

Study limitations

Finally, our study has some limitations. As with any estimates after matching analysis, the temporal and spatial effects are potentially biased by unmeasured covariates unrelated to the observed covariates (Stuart, 2010). Nevertheless, the sensitivity analyses offer a transparent assessment regarding the influence required from unmeasured covariates to explain away our current estimates. The observed covariates still create a general classification of accessibility and forest loss pressures and control for spatial location. Despite using stratified sampling matching, known to effectively reduce covariate imbalances and the variability of treatment effects (e.g., temporal and spatial effects) (Iacus et al., 2019), further research would benefit from comparing stratified and random sampling matching. We also aimed to identify the overall influence of ITs, OAs, and PAs across neotropical forests to solve the limited geographical scales and homogeneous pressures on forest loss in similar studies (Börner et al., 2020). However, these tenure categories represent different and diverse realities in each country. For instance, OAs in Colombia are subject to a policy that requires National Park Authorities to establish co-management agreements with Indigenous communities

(Unidad Administrativa del Sistema de Parques Nacionales Naturales, 2001), which is not necessarily the case in other countries. Even in subnational scales, PAs comprise a broad spectrum of restrictions, local agents, and land use dynamics (Blackman, 2015; Radachowsky et al., 2012). Moreover, the geographic discontinuity designs and linear mixed models account for the influence of local or geographically restricted effects, but they do not incorporate the influence of external interventions such as REDD+ and payments for ecosystem services. Future studies could exploit the advantages of matching analysis and geographic discontinuity designs to explore the influence of PAs' restrictions and external interventions. Finally, the outcome variable also brings limitations because it does not differentiate carbon stock losses due to deforestation and degradation; rather, it provides a comprehensive measure (i.e., aboveground carbon stocks) that captures forest conservation effectiveness beyond deforestation.

Conclusions

After controlling the influence of spatial location, we found that ITs and OAs with decentralized forest governance represent effective Natural Climate Solutions. Particularly, these indigenous lands and PAs have similar temporal and spatial effects on carbon stocks in Panama and Amazon Basin countries. Considering that the observation units sampled by matching are located along the boundaries of these land tenures, the temporal and spatial effects are conservative. Consequently, our findings show that Indigenous Peoples are supporting Nationally Determined Contributions (NDCs) under the Paris Agreement. Brazil and Ecuador expect to receive their first results-based payments from the Green Climate Fund corresponding to 96.5 and 18.6 million USD, respectively (Maniatis et al., 2019). For the critical role they play in reducing net carbon emissions, Indigenous Peoples must become recipients of such benefits, independent of the opportunity costs of avoided deforestation and degradation (Karsenty et al., 2014).

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Linking Statement 1

Chapter 1 revealed the effect of Indigenous Territories, Protected Areas, and their overlaps (i.e., Overlapped Areas) on carbon stocks using a spatial-temporal approach and Other Lands (private or public lands lacking protection) as counterfactuals. The results demonstrate that Indigenous Territories and Overlapped Areas (i.e., Indigenous Lands) preserve carbon stocks and buffer losses, as well as Protected Areas, in Panama and Amazon Basin countries. The effects of Indigenous Territories and Overlapped Areas suggest that Indigenous Peoples' land use may have a limited and stable impact on the domestic forests' carbon stocks through time and space. Nevertheless, Chapter 1 did not explore the different management categories and the potential heterogeneous effects of PAs, some of which governments have partially devolved forest governance to Local Communities (i.e., Community Managed PAs). Additionally, Chapter 1 did not analyze the influence of external policy interventions that could influence land use and carbon stocks changes. Chapter 2 explores these limitations and aims to address the effectiveness of Community Managed PAs on forest carbon dynamics before and after adopting REDD+ programs, an external policy intervention. Compared to Chapter 1, the effectiveness of Community Managed PAs is determined using multiple categories of counterfactuals.

Chapter 2: Community Managed Protected Areas conserve aboveground carbon stocks: Implications for REDD+

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Keywords: carbon stocks, avoided carbon emissions, protected areas, forest communities, REDD+, matching analysis, geographic discontinuity designs.

Abstract

Protected Areas (PAs) represent a broad spectrum of outcomes and governance systems. Among PAs, Community Managed PAs have emerged from communities that are not exclusively indigenous and have developed social organizations to acquire land rights, participate in forest governance, and in some cases, engage in REDD+. However, regardless of the scale or counterfactual, there is no clear consensus about Community Managed PAs' effectiveness in forest conservation and climate change mitigation. Furthermore, previous studies have been devoted to estimating PAs' effects on deforestation before REDD+ projects began to operate. Based on Community Concessions in Petén (Guatemala) and Extractive Reserves in Acre (Brazil), we analyzed Community Managed PAs' temporal and spatial effects on carbon stocks and avoided emissions relative to unprotected lands, other Sustainable Use PAs (IUCN V-VI), and Strict PAs (I-IV). We used carbon density maps, matching methods, geographic discontinuity designs, and sensitivity analysis between 2003 and 2015. After controlling for the influence of market access and agriculture suitability, our analysis shows that Community Managed PAs were more effective than Other Lands (i.e., unprotected) and Sustainable Use PAs, and at least as effective as Strict PAs, in preserving carbon stocks and avoiding emissions. For instance, relative to Other Lands between 2011 and

2015, Community Managed PAs resulted in net avoided emissions of 4.6 tCO2-eq/ha in Petén (Guatemala) and 2.15 tCO2-eq/ha in Acre (Brazil). While these net avoided emissions were lower than in previous years, they seem to be driven by a reduction in carbon emissions outside Community Managed PAs. Spatially, the boundaries of Community Managed PAs varied across jurisdictions. For example, the boundaries of Acre's Community Managed PAs' have become less effective in avoiding emissions, which translates into reduced effects on conserving carbon stocks. Our results highlight the need to assess temporal effects to exhibit jurisdiction-wide land-use dynamics and spatial effects to identify local land-use pressures emerging inside or around the boundaries of PAs. Our analysis also shows that decentralized governance in Community Managed PAs may contribute to climate change mitigation through REDD+ and forest conservation targets.

Introduction

Protected Areas (PAs) remain as primary interventions for forest conservation (Börner et al. 2020). In practice, PAs represent a broad spectrum of governance systems with outcomes beyond forest conservation (Dudley et al. 2010). To account for the different outcomes of PAs, the IUCN developed a number of categories. Those classified in categories I-IV, or Strict PAs, privilege biodiversity conservation and limit extractive activities through state-based forms of governance. Sustainable Use PAs, classified in categories V-VI, represent a more direct interaction between ecosystems and people, integrating biodiversity conservation and non-industrial extractive activities under more decentralized forms of governance. Since the 1980s, the decentralized governance of some Sustainable Use PAs has resulted in Community Managed PAs, an intervention aiming to reduce the financial costs of conservation and recognize forest communities' livelihoods, management practices, and social organizations (Agrawal et al. 2008). Considering that climate change mitigation through avoided land-use emissions has become a primary goal for PAs (MacKinnon et al. 2011), Community Managed PAs represent an intervention where multiple social and ecological outcomes converge.

Despite the potential win-win outcomes of Sustainable Use PAs, especially in those that are Community Managed, their effectiveness in forest conservation and climate change mitigation can be put into question. For example, Walker et al. (2020) found that non-Strict PAs in the Brazilian Amazon were responsible for more than 90% of forest carbon losses in PAs. Although counterintuitive, the fact that Sustainable Use PAs or Community Managed PAs may exhibit higher carbon losses than Strict PAs does not necessarily imply that they are not effective. Strict PAs might be experiencing low deforestation (and forest degradation) because of their reduced market access and suitability for agriculture (Pfaff et al. 2014). Hence, if the influence of spatial location is considered, are Community Managed PAs effective in forest conservation and climate change mitigation?

To address this question, different studies use quasi-experimental methods to evaluate PAs' effects on forest conservation. The premise of these studies is to remove the influence of market access and agriculture suitability by equating the distribution of spatial location covariates (e.g., distance to cities) in PAs and some counterfactual (Joppa and Pfaff 2009; 2010). In the tropics, some of these studies have shown that Strict PAs are more effective than Sustainable Use PAs in forest conservation (Ferraro et al. 2013; Jusys 2018; Pfaff, Robalino, Sandoval, et al. 2015; Nolte et al. 2013; Bonilla-Mejía and Higuera-Mendieta 2019; Elleason et al. 2021), while others have shown the opposite (Andam et al. 2013; Blackman et al. 2015; Nelson and Chomitz 2011). Despite the lack of consensus, the previous studies offer relevant highlights to assess PAs' effectiveness in forest conservation and climate change mitigation. First, an integral assessment of PAs requires measuring their effectiveness not only relative to unprotected Other Lands (i.e., but also relative to other PAs categories (e.g., Andam et al., 2013; Elleason et al., 2021; Ferraro et al., 2013). For example, using Other Lands and different PA categories as counterfactuals of Community Managed PAs. These multiple comparisons are particularly relevant to account for differences in spatial location among Community Managed PAs, Sustainable Use PAs, Strict PAs, and Other Lands (Pfaff et al. 2015; Pfaff et al. 2014). Moreover, certain studies focus on the temporal effects. That is, estimating deforestation or regrowth inside and outside PAs for a time period. However, other studies (e.g., Bonilla-Mejía & Higuera-Mendieta, 2019), assess the role of PAs boundaries relative to their surroundings or the spatial effects to elucidate local land-use dynamics. Thus, estimating temporal effects alongside spatial effects may contribute to the integral assessment of PAs (Alejo et al. 2021; Blackman et al. 2015). Nevertheless, few studies evaluate the effectiveness of Community Managed PAs relative to different land tenures through temporal and spatial assessments.

Some quasi-experimental studies have focused on Community Managed PAs. Typically, Community Managed PAs have emerged from communities that are not exclusively indigenous and have developed social organizations to acquire land rights, access to forest livelihoods, and participate in forest governance (Cronkleton et al. 2008). Two foundational research efforts shed light on the effectiveness of Community Managed PAs in the 2000s. Relative to Other Lands, Blackman et al. (2015) established in the Maya Biosphere Reserve (Petén, Guatemala) that Sustainable Use PAs were more effective than Strict PAs in avoiding deforestation, and among Sustainable Use PAs, Community Concessions (a form of Community Manage PAs) were the most effective. Pfaff et al. (2014) provide a similar insight and exhibit that among Strict PAs, Indigenous Territories, and Extractive Reserves (another form of Community Managed PAs), the latter was the only land tenure with significant impacts on avoided deforestation (Pfaff et al. 2014). However, the context of Community Managed PAs in Petén (i.e., Community Concessions) and Acre (i.e., Extractive Reserves) have experienced changes that may have influenced their role in forest conservation and climate change mitigation. In both jurisdictions, new Strict and Sustainable Use PAs have been declared (UNEP-WCMC and IUCN 2021), creating an even more complex mosaic of PAs and Other Lands. Regarding Petén, some Community Managed PAs have lost their status while others have consolidated and became proponents on a pioneer jurisdictional REDD+ program in 2012 (Hodgdon et al. 2013). In the same year, the state of Acre began to implement a System of Incentives for Environmental Services

(SISA) that also includes a pioneer REDD+ program (Rosa Da Conceição and Börner 2020). Thus, it becomes crucial to provide an updated and integral assessment to this pioneer Community Managed PAs in the context of climate change mitigation and REDD+.

Consequently, our study aims to assess the effectiveness of Community Managed PAs on forest carbon dynamics before and after the adoption of REDD+ programs in 2012 using two case studies: Community Concessions in the Department of Petén (Guatemala) and Extractive Reserves in the State of Acre (Brazil). Particularly, we assess Community Managed PAs' effect on carbon stocks and avoided carbon emissions relative to Other Lands, Sustainable Use PAs, and Strict PAs. Our assessment relies on carbon density maps, matching methods, and geographic discontinuity designs to measure the temporal and spatial effects of Community Managed PAs between 2003 and 2015. After controlling for market access and agriculture suitability covariates, our results show that Community Managed PAs in Petén and Acre are temporally effective in preserving larger carbon stocks and avoiding carbon losses. However, these effects have been reducing in time and becoming less robust to unobserved covariates. The spatial effects indicate that Community Managed PAs' boundaries have varied effects on carbon dynamics related to the geographic settings of Petén (Guatemala) and Acre (Brazil).

Our study differs from previous research on PAs and quasi-experimental methods in multiple ways. Compared with studies that estimate the effectiveness of PAs using either Other Lands (e.g., Nelson and Chomitz 2011; Alejo et al. 2021) or other PAs (e.g., Elleason et al., 2021) as counterfactuals, we estimate Community Managed PAs' effectiveness relative to multiple land tenures. Moreover, we explore this effectiveness temporally and spatially on carbon stocks and avoided emissions, contrasting similar studies that usually explore one of these two approaches on deforestation (e.g., Baragwanath & Bayi, 2020; Blackman & Veit, 2018; Bonilla-Mejía & Higuera-Mendieta, 2019; Miranda et al., 2016). Finally, our focus on Community Managed PAs' effects on carbon stocks dynamics exceeds the time frame of previous studies in Petén and Acre (i.e., Blackman, 2015; Pfaff et al., 2014) and explores the influence of forest communities and decentralized governance on climate change mitigation and REDD+.

Materials and Methods

Study Areas

Our study assesses Community Managed PAs in two subnational jurisdictions from the Neotropics: Petén, a department in northern Guatemala, and Acre, a state in Brazil's western Amazon (Figure 1, Supplementary Material, Table S1). The predominant ecosystems are two types of tropical moist forests: the Petén-Veracruz for the former and the Southwest Amazon for the latter (Olson et al. 2001). Petén and Acre correspond to particular social, political, and geographic settings, but share at least, four factors in common: (1) policies and investments in forest conservation for more than three decades, (2) diverse land tenures involved in forest governance, (3) social organizations that emerged from forest communities, and (4) being pioneers in REDD+ programs.

In Petén, the Maya Biosphere Reserve was established in 1990 under the pressure of environmental and international aid organizations to curb deforestation, resulting in the delimitation of strict PAs, Multiple Use Zones (here, Sustainable Use PAs), and a buffer zone (Radachowsky et al. 2012). The new reserve created tensions between the PAs service (CONAP) and past-resident communities (Cronkleton et al. 2008). These tensions escalated with the arrival of new residents after the Guatemalan peace accords and the interest of private enterprises to acquire forest concessions in Multiple Use Zones (Cronkleton et al. 2008). Supported by environmental and international aid organizations, ACOFOP ("Asociación de Comunidades Forestales de Petén") emerged as a social organization to negotiate the access of past, new resident, and non-resident communities to forest concessions and guarantee local livelihoods (Millner et al. 2020). Between 1994 and 2002, the negotiations granted access to Multiple Use Zones in the

Maya Biosphere Reserve to community concessions, private concessions, and cooperatives (Radachowsky et al. 2012). More recently, the department of Petén extended its PAs network outside the Maya Biosphere Reserve with public and private areas with strict protection (IUCN I-IV) and sustainable use (IUCN V-VI) (UNEP-WCMC and IUCN 2021).

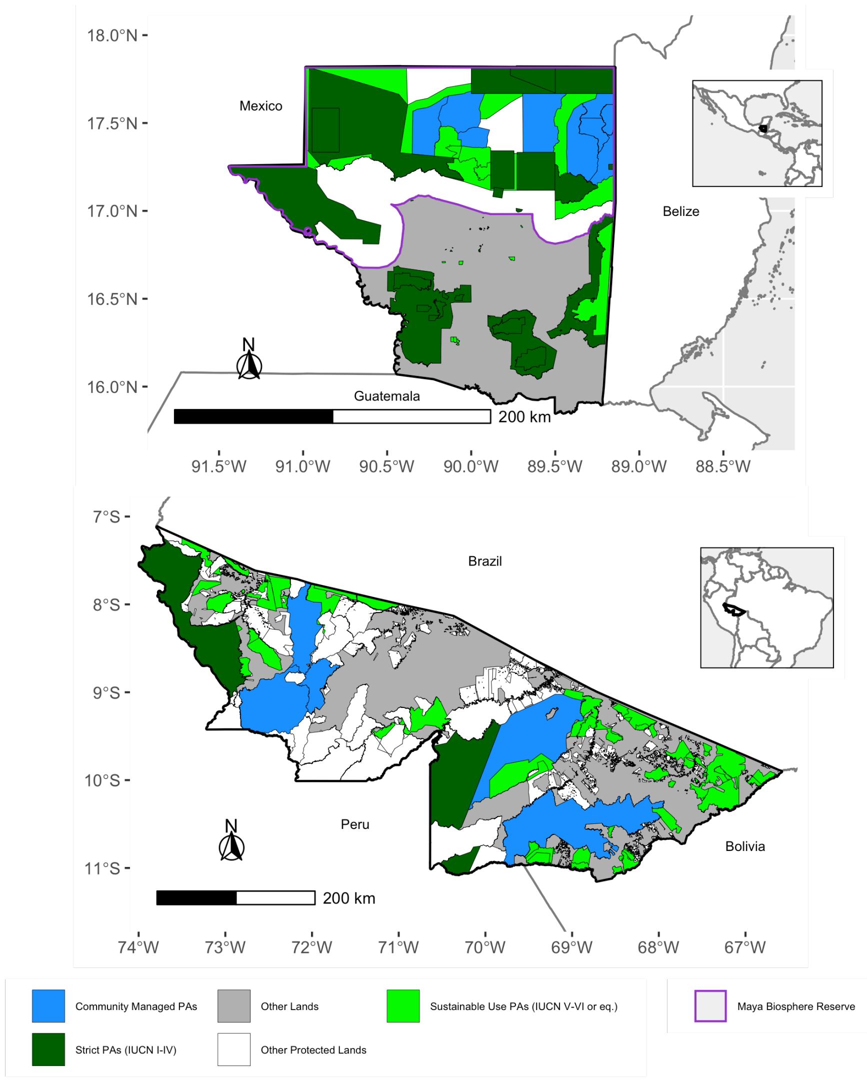

Figure 1. Study Areas. (A). The department of Petén in Guatemala (Central America) (B). The state of Acre in Brazil (South America). Land tenure is classified as Community Managed PAs (blue), which correspond to Community Concessions in Petén and Extractive Reserves in Acre, Other Lands (gray), Sustainable Use PAs (light green), Strict PAs (dark green), and Other Protected Lands (white).

We classify these multiple land tenures in different PA categories (Table 1A). PAs that allow indirect uses (IUCN I-IV) are defined as Strict PAs. PAs with IUCN categories V-VI and revoked community concessions, cooperatives, and Multiple Use Zones in the Maya Biosphere Reserve are categorized as Sustainable Use PAs. The Maya Biosphere Reserve's buffer zone, which does not fit our definitions of PAs, and Private Concessions, which belong to ACOFOP but do not involve forest communities, are excluded from our study. We focus on eight Community Managed PAs, here defined as Community Concessions in the Maya Biosphere Reserve that have remained active and certified. Among these Community Managed PAs, one is inhabited by new residents (Cruce a la Colorada), two by past residents (Carmelita and Uaxactún), and the rest belong to non-resident communities that live outside the Maya Biosphere Reserve. Also relevant for our study, these Community Managed PA's became proponents with the PAs service (CONAP) of the REDD+ program GuateCarbon since 2012 (Hodgdon et al. 2013). GuateCarbon aims to offset 33 million tons of CO2-eq from avoided deforestation over a 30-year life span applying a baseline that involves the department of Petén and models future deforestation based on key variables such as roads, population density, markets, and development plans (Hodgdon et al. 2013; Verra 2017).

The state of Acre in the Brazilian Amazon has also developed conservation policies and social organizations that emerged from forest communities. During the 1970's the expansion of cattle ranching and land speculation in the Brazilian amazon created conflicts with rubber tappers and concern among environmental organizations (Cronkleton et al. 2008; Rosa Da Conceição and Börner 2020). A converging pressure from environmental organizations, the growing social movement of rubber tappers to defend their lands and livelihoods, and the later assassination of rubber tapper leader Chico Mendes in 1988 influenced the creation of two federal Extractive Reserves in Acre (Rosa Da Conceição and Börner 2020).

	Protected Areas (PAs)			
Jurisdiction	Community Managed (IUCN IV-VI or equivalent)	Sustainable Use (IUCN IV-VI or equivalent)	Strict (IUCN I-IV or equivalent)	Other Protected Lands (Excluded from the study)
Peten (Guatemala)	Community Concessions (Active)1,2 :	Community Concessions (revoked or suspended managed plans)1,2	National Parks	Private Concessions1,2
		Special use zones - ZUM1,2	Regional Municipal Park	Buffer Zone1,2
	San Andrés, Carmelita, Cruce a la Colorada, Uaxactún, Chosquitán, Las Ventanas, La Unión, Yaloch	Cooperatives1,2	Wildlife refugee	
		Private Natural Reserves	Protected Biotopes	
		Biosphere Reserves	Biological Reserves	
			Natural Monuments	
			Cultural Monuments1,2	
Acre (Brazil)	Extractive Reserves (RESEX):	National Forests	National Parks	Indigenous Territories2
		State Forests	State Parks	Indigenous Territories/PAs overlaps
		Environmental Protection Area	Area of relevant ecological interest	Undesignated Public Forests2
	Chico Mendes, Cazumbá-Iracema, Alto Juruá, Alto Tarauacá, Riozinhno da Liberdade	Directed Settlement Projects - PAD2,3	Ecological Station	
		Agroextractive Settlement Project - PAE2,3		
		Sustainable Development Project - PDS2,3		
		Forest Settlement Project - PAF2,3		

Table 1. Protected Area (PAs) categories included in the department of Petén (Guatemala) and the state Acre (Brazil). Community Managed PAs are a subcategory of Sustainable Use PAs that was analyzed independently. [1]Maya Biosphere Reserve, [2]No official IUCN category, [3]Settlements in Public Forests.

Since the 1990s, the state of Acre developed policies that incentivized investments in sustainable economic activities, economic and ecological zoning (Pfaff et al. 2014), and in 2010 established the System of Incentives for Environmental Services (SISA) that relies on international and national funding (Rosa Da Conceição and Börner 2020; Sills et al. 2014). This system includes a pioneer jurisdictional REDD+ program, ISA-carbono, which involved payments for demonstrated emission reductions between 2012 and 2015 for the first implementation phase (Sills et al. 2014; Rosa Da Conceição and Börner 2020). Since 2017, the second phase of ISA-Carbono has been under implementation (IMC 2020). The program includes as beneficiaries forest extractivists (including rubber tappers), indigenous communities, and small colonist farmers (Sills et al. 2014). Furthermore, these policies led to the declaration of multiple PAs, including strict PAs (IUCN V-VI) such as National Parks, State Parks, and Environmental Protection Areas. There is also a diverse group of PAs that allow sustainable use, here defined as Sustainable Use PAs, including IUCN VI PAs (e.g., National and State forests) and settlements in public forests that lack an IUCN status. Considering that our study focuses on non-indigenous forest communities, we do not assess Indigenous Territories and their overlaps with PAs. Undesignated public forests are also excluded from the study because they are not considered PAs (Serviço Florestal Brasileiro 2020). As active Community Concessions in Petén (Guatemala), we define Extractive Reserves in Acre (Brazil) as Community Managed PAs, given the relatively unified social organizations behind the establishment of these areas (Millner et al. 2020; Cronkleton et al. 2008; Gomes et al. 2018). We include the following five Extractive Reserves in our study: Chico Mendes, Cazumbá-Iracema, Alto Juruá, Alto Tarauacá, and Riozinhno da Liberdade. Finally, any public and private land that is not categorized as PA, buffer zone, Indigenous Territory, or Private Concessions was defined as Other Land.

Spatial data and processing

PAs and other land tenures were spatially delineated from multiple sources (Table 2). The World Database on Protected Areas (UNEP-WCMC and IUCN 2021) was used to establish the boundaries and IUCN categories of Strict PAs and some Sustainable Use PAs in Petén (Guatemala) and Acre (Brazil). The boundaries and status of Community Managed PAs (i.e., Community Concessions) and Sustainable Use PAs in the Maya Biosphere Reserve (Petén) were confirmed from data curated by ACOFOP. Indigenous Territories and their overlaps with PAs in Acre were defined from data curated by RAISG (Amazon Geo-referenced Socio-Environmental Information Network). The 'Cadastro nacional de florestas públicas' (National survey of public forests) from the Brazilian government allowed to identify settlements in public forests (Sustainable Use PAs) and undesignated public forests (Serviço Florestal Brasileiro 2020). These geospatial datasets defined land tenure and, therefore, the treatment group (i.e., Community Managed PAs) and control groups (Other Lands, Sustainable Use PAs, and Strict PAs).

In our statistical analyses, annual carbon stocks and avoided land-use carbon emissions were the response variables. We determined carbon stocks dynamics in both Petén (Guatemala) and Acre (Brazil) from annual carbon density maps (~500 m resolution) generated by the Woodwell Climate Research Centre between 2003 and 2015 (Baccini et al. 2021) and explained in detail by Baccini et al. (2012; 2017) and Walker et al. (2020). This time frame is segmented in three time periods: 2003-2007, 2008-2011, and 2012-2015. The first period is Pre-REDD+ considering that the program was launched at the Bali COP in 2007. We define the second period as REDD+-Readiness due to the international coordination that led to MRV systems (Monitor, Report and Verify) and safeguards that influenced the design of GuateCarbon in Petén (Guatemala) and ISA-Carbono in Acre (Brazil) before 2012. Finally, the latest period, REDD+ implementation, corresponds to the beginning of the crediting period of GuateCarbon and the first payments for demonstrated emission reductions in ISA-Carbono.

Jurisdiction	Geospatial Information	Time period	Source
Petén (Guatemala)	Community Concessions, Private Concessions, and Cooperatives	2002-2018	ACOFOP
	Protected Areas	2002-2020	UNEP-WCMC & IUCN (2021)
Acre (Brazil)	Indigenous Territories	2002-2018	RAISG (Red Amazónica de Información Socio-Ambiental Geo-Referenciada)
	Protected Areas	2002-2015	RAISG, UNEP-WCMC & IUCN (2021), Cadastro Nacional de florestas públicas (2020)
Both jurisdictions	Annual carbon density (tC/ha)	2003-2015	Woodwell Climate Research Center (Baccini et al. 2012; 2017; 2021)
	Elevation (m) and slope (deg.)	NA	CGIAR-SRTM V4 (Jarvis et al. 2008; Reuter et al. 2007)
	Mean precipitation (mm/year) and mean temperature (°c/year)	1970-2000	WorldClim V2.1 (Fick and Hijmans 2017; 2020)
	Population density - UN adjusted (people/km^2)	2002, 2007, 2011	Worldpop et al. (2020)
	Travel time to the nearest city of 50,000 or more people	2000	Nelson et al. (2008)
	Travel time to the nearest city of 50,000 or more people	2015	Weiss et al. (2018)

Table 2. Geospatial data included in the study.

Agriculture suitability and market access conditions were used as spatial location covariates associated with carbon stocks dynamics in Petén (Guatemala) and Acre (Brazil) (Table 2). Elevation, slope, precipitation, and temperature were included as spatial location covariates involved in agricultural suitability, following previous quasi-experimental studies (Blackman and Veit 2018; Blackman 2015; Alejo et al. 2021; Pfaff et al. 2014). Elevation and slope were obtained from CGIAR-SRTM Version 4 (Reuter et al. 2007; Jarvis et al. 2008). 30-year (1970-2000) mean average precipitation and temperature were obtained from WorldClim's Version 2.1 (Fick and Hijmans 2017; 2020). Additionally, we included population density and travel time to the nearest city, which have been used to control the influence of market access (Nelson and Chomitz 2011; Negret et al. 2020). We determined population density in 2002, 2007 and 2011 from the Worldpop database (Worldpop et al. 2020). Travel time to cities with more than 50000 people was obtained from Nelson et al. (2008) in 2000 and Weiss et al. (2018) in 2015. By resampling tenure and covariate data to carbon density maps' spatial resolution (~500 m), we created observation units with carbon density estimates, land tenure, and covariates. The Supplementary Material summarizes the carbon stocks (Table S2), total carbon storage (Table S3), agriculture suitability (Table S4), and market access data (Table S5) for each jurisdiction and land tenure. All geoprocessing was performed with the R packages sf (Pebesma, Bivand, et al. 2021) and stars (Pebesma, Summer, et al. 2021).

Matching Analysis

To control for spatial location and infer the effectiveness of Community Managed PAs on carbon stocks dynamics relative to Other Lands, Sustainable Use PAs, and Strict PAs, we performed matching analysis and linear mixed models following Alejo et al. (2021). Matching analysis removes heterogeneous observations and creates a subset of treatment and control observations with similar covariate values, reducing the association of a treatment variable with covariates (Diamond and Sekhon 2012). Here, the treatment variable corresponded to areas designated as Community Managed PAs, and matching created subsets of observations in the treatment and control (i.e., Other Lands, or Sustainable Use PAs, or Strict PAs) with similar slope, elevation, precipitation, temperature, population density, and time travel to cities. Thus, matching analysis was applied to compare Community Managed PAs with Other Lands, Sustainable Use PAs, and Strict PAs independently. Additionally, matching analysis was performed in the three time periods aforementioned: 2003-2007, 2008-2011, and 2012-2015.

Each matching analysis only included PAs that were established at least a year before a time period. It is worth noting that the extent of Community Managed PAs increased 5.5% during the second time period in Acre but did not vary in Petén (Supplementary

Material, Table S1). Similarly, population density estimates corresponded to the previous year in a time period (e.g., 2002 population density to 2003-2007). Regarding time travel to cities, the 2000's estimates were applied for the periods 2003-2007 and 2008-2011, while the 2015's estimates were applied for 2012-2015. Using different time periods guarantees an accurate, updated, and conservative assessment of Community Managed PAs' performance that accounts for changes in land tenures extents and changing conditions in covariates. All matching analyses were performed through coarsened exact matching (CEM) (Iacus et al. 2015) in the R package MatchIt (Ho et al. 2015) that allows users to define intervals of equivalent covariate values. For instance, the travel time to cities was restricted to 60 minutes intervals, making travelling times between 61 minutes and 120 minutes 'equivalent'. CEM's approach created a subset of observations with a covariate balance between Community Managed PAs (i.e., the treatment) and each control in Petén (Guatemala) and Acre (Brazil). The unmatched and matched covariate balances were assessed through standardized mean differences and variance ratios (Stuart 2010) using the R package Cobalt (Greifer 2021).

Temporal effects on carbon stocks dynamics

After matching analysis, we used linear mixed models to estimate the temporal effect of Community Managed PAs on carbon stocks and avoided carbon emissions relative to Other Lands, Sustainable Use PAs, and Strict PAs. The effects of Community Managed PAs on carbon stocks derived from the general expression:

$$\mathbf{y_t} = \mathbf{b_{0t}} + \mathbf{b_{1t}x_p} + \boldsymbol{\beta}\mathbf{Z_p} + \boldsymbol{\alpha}_\mathbf{p} + \mathbf{e_t} \quad (1)$$

where y_t corresponded to carbon density in year t, the outcome variable, and b_{0t} was the fixed intercept. b_{1t} and x_p were the fixed effect slope in year t and predictor of the treatment in the period p (i.e., a dummy for Community Managed PAs), respectively. β was a vector of additional fixed effects for a vector of predictors Z_p, containing the covariates elevation, slope, temperature, precipitation, population density, and travel time to cities. Including the covariates as fixed effects span any remaining imbalances from the matched subsets, providing further control on the influence of market accessibility and agricultural suitability, and therefore, conservative estimates of

Community Managed PAs' effects on carbon stocks dynamics. The matched sub-group (matched observation units in treatments and control with similar covariate values) was the random effect $\mathbf{e_t}$ to account for the structure of the matched subsets. We slightly modified the previous expression to calculate the avoided carbon emissions as:

$\Delta \mathbf{y_p} = \mathbf{b_{0p}} + \mathbf{b_{1p}x_p} + \boldsymbol{\beta}\mathbf{Z_p} + \boldsymbol{\alpha}_\mathbf{p} + \mathbf{e_p}$ (2)

In this case, $\Delta \mathbf{y_p}$ represents the net change in carbon density for a time period p of four years. The linear mixed models in (1) were estimated annually in 2007, 2011, and 2015 and the linear mixed models in (2) were estimated in 2003-2007, 2007-2011, and 2011-2015. We focused on two parameters in (1) and (2) to estimate the temporal effect of Community Managed PAs on carbon stocks and avoided carbon emissions. The fixed effects intercept b_{ot} in (1) refers to the average annual carbon density found in the controls (i.e., Other Lands, Sustainable Use PAs, or Strict PAs) and represent the carbon stocks baselines for Community Managed PAs. b_{1t} (1) refers to the annual average differences of carbon stocks between the treatment (i.e., Community Managed PAs) and the controls. Thus, a positive effect in (1) implies that Community Managed PAs would store higher carbon stocks than a given control after controlling for spatial location. Regarding (2), the fixed effects intercept b_{op} refers to the average change in carbon density found in the controls. b_{1p} (2) compares the average change of carbon stocks in the treatment and the control group over a four years period. A positive effect in (2) transformed to CO_2-eq implies that Community Managed PAs avoided more carbon emissions than a given control after controlling for spatial location. In other words, the temporal effects derived from the matching analysis together with the linear mixed models allowed us to estimate if Community Managed PAs stored larger carbon stocks and avoided more CO_2-eq emissions than Other Lands, Sustainable Use PAs, and Strict PAs.

Spatial effects on carbon stocks dynamics

To estimate the spatial heterogeneity of the temporal effects, we used geographic discontinuity designs. Following Keele & Titiunik (2015) and similar to Alejo et al. (2021), the geographic discontinuity designs aimed to estimate the effect of Community

Managed PAs boundaries on preserving carbon stocks and avoiding CO_2-eq emissions (hereafter, spatial effects) relative to surrounding Other Lands, Sustainable Use PAs, and Strict PAs. These geographic discontinuity designs are based on two assumptions. First, the treatment assignment occurs as-if randomized when controlling for covariates and geographic distance (i.e., the distance among treatment and control observations throughout a boundary) (Keele et al. 2015). Derived from the first assumption, the second assumption establishes that the spatial effect is a function of the treatment of interest (Keele and Titiunik 2015), implying that Community Managed PAs boundaries influence carbon stocks and CO_2-eq emissions.

The assumptions above were supported by employing CEM to find treatment and control observations with the equivalent covariates (i.e., slope, elevation, temperature, precipitation, population density, and travel time to the nearest city) and additionally including the geographic distance. Particularly, we controlled for geographic distance by performing matching analyses throughout four buffer zones inside and outside the boundaries of Community Managed PAs: 0–1 km, 0–5 km, 0-10 km, and 0–15 km. We chose these distances based on previous studies showing that natural vegetation (Joppa et al. 2008) and carbon stocks (Alejo et al. 2021) increase inside the boundaries of PAs and stabilize at ~15 km. Thus, when matching treatment and control observations in buffer zones 0–1 km, we included matches across a 2-km radius. Similarly, in 0–15-km buffer zones, we matched observations across a 30-km radius. As the temporal effects, the covariate balance before and after matching in the four buffer zones was assessed through standardized mean differences and variance ratios. As suggested by Keele et al. (2015), we provided further support to the geographic discontinuity designs by performing falsification tests. These tests imply that each covariate in Z_p was treated as an outcome variable y_p according to the linear mixed models above. The falsification tests showed that Community Managed PAs ($\mathbf{x_p}$) had negligible effects on the covariates ($\mathbf{b_{1p}}$) after matching. These geographic discontinuity designs guarantee that observations inside and outside the boundaries of Community Managed PAs will occur as-if randomized and be valid counterfactuals by sharing a distance to boundaries (e.g., 0-1 km), covariate values (e.g., 0-60 minutes travel distance to cities), and geographic distance (e.g., 2 km radius). Furthermore, if the assumptions above hold across the multiple buffer distances to Community Managed PAs boundaries, it is possible to estimate the heterogeneity of the spatial effects. This heterogeneity represents the variation of carbon stocks and avoided carbon emissions as the distance to Community Managed PAs' boundaries increase.

Sensitivity Analysis

Combining matching analysis and linear models, like those mentioned above, controls the effects of observed covariates and others unobserved but correlated (Stuart 2010). We used sensitivity analyses to assess the effect of unobserved covariates unrelated to the observed covariates but related to the treatments and their effects (Liu et al. 2013). Specifically, we estimated the E-Value as applied in Alejo et al. (2021) with the R package Evalue (Mathur et al. 2021) for all spatial and temporal effects. The E-value is a metric that represents the minimum strength that an unmeasured covariate would need to have with the treatment and its effect for the treatment and effect association not to be causal (VanderWeele and Ding 2017). Following the procedure justified by VanderWeele & Ding (2017), the E-value derives from estimating the Effects Ratio (ER), which at the same time derives from the temporal and spatial effects. In our study, the temporal and spatial effects are transformed into an Effects Ratio (ER) (equivalent to a risk ratio in the epidemiological literature) that compares the probability of a positive effect in the treatment with the probability of a positive effect in the control. ERs greater than 1 indicate a greater probability that Community Managed PAs will store higher carbon stocks or avoid larger emissions than Other Lands, Sustainable Use PAs, or Strict PAs. For instance, a hypothetical ER of 2 may imply that Community Managed PAs are two times more likely to avoid higher carbon emissions than Other Lands. Following this hypothetical case, an E-value of 3 indicates that the ER of 2 could be explained away by an unmeasured covariate that was associated with both Community Managed PAs and carbon emissions each by 3-fold, above and beyond the observed covariates. At the same time, an E-value lower than 3 could not alter the ER, and consequently, the temporal effect of Community Managed PAs. In other words, the E-value assesses the strength of an unobserved covariate to alter the temporal and spatial effects of Community Managed PAs on carbon stocks dynamics. All geospatial and statistical analyses aforementioned were performed in R version 4.1.0 (R Core Team 2021).

Results

We estimated the effectiveness of Community Managed PAs on carbon stocks dynamics temporally and spatially relative to Other Lands (i.e., unprotected), Sustainable Use PAs (IUCN V-VI or equivalent), and Strict PAs (IUCN I-IV) in Petén (Guatemala) and Acre (Brazil). Before controlling for market access and agriculture suitability covariates, Community Managed PAs in both jurisdictions throughout 2003 and 2015 stored > 20 tC/ha compared to Other Lands, > 10 tC/ha compared to Sustainable Use PAs, and < 10 tC/ha compared to Strict PAs (Supplementary Material, Table S2). However, these land tenures are not directly comparable, as they are subject to different levels of market access and agriculture suitability (Figure 2, Supplementary Material, Tables S4 and S5). For example, Petén's mean population density in Strict PAs and Other Lands was nearly five times (~11 people/km^2) and ten times (~23 people/km^2) higher than Community Managed PAs (~2.5 people/km^2) in 2002, respectively. Similarly, travel times to cities in 2000 in Acre ranged between 17 hours in Sustainable Use PAs to 39 hours in Community Managed PAs. Furthermore, the influence of these spatial location covariates changes at different paces depending on land tenure. For instance, in Petén, Community Managed PAs travel time to cities in 2015 reduced by 20 minutes compared to 2000. However, the same comparison in Other Lands led to a reduction of 3 hours in travel time. These differences show that spatial location covariates influencing carbon stocks dynamics even vary among Community Managed PAs and other categories of PAs in Petén and Acre.

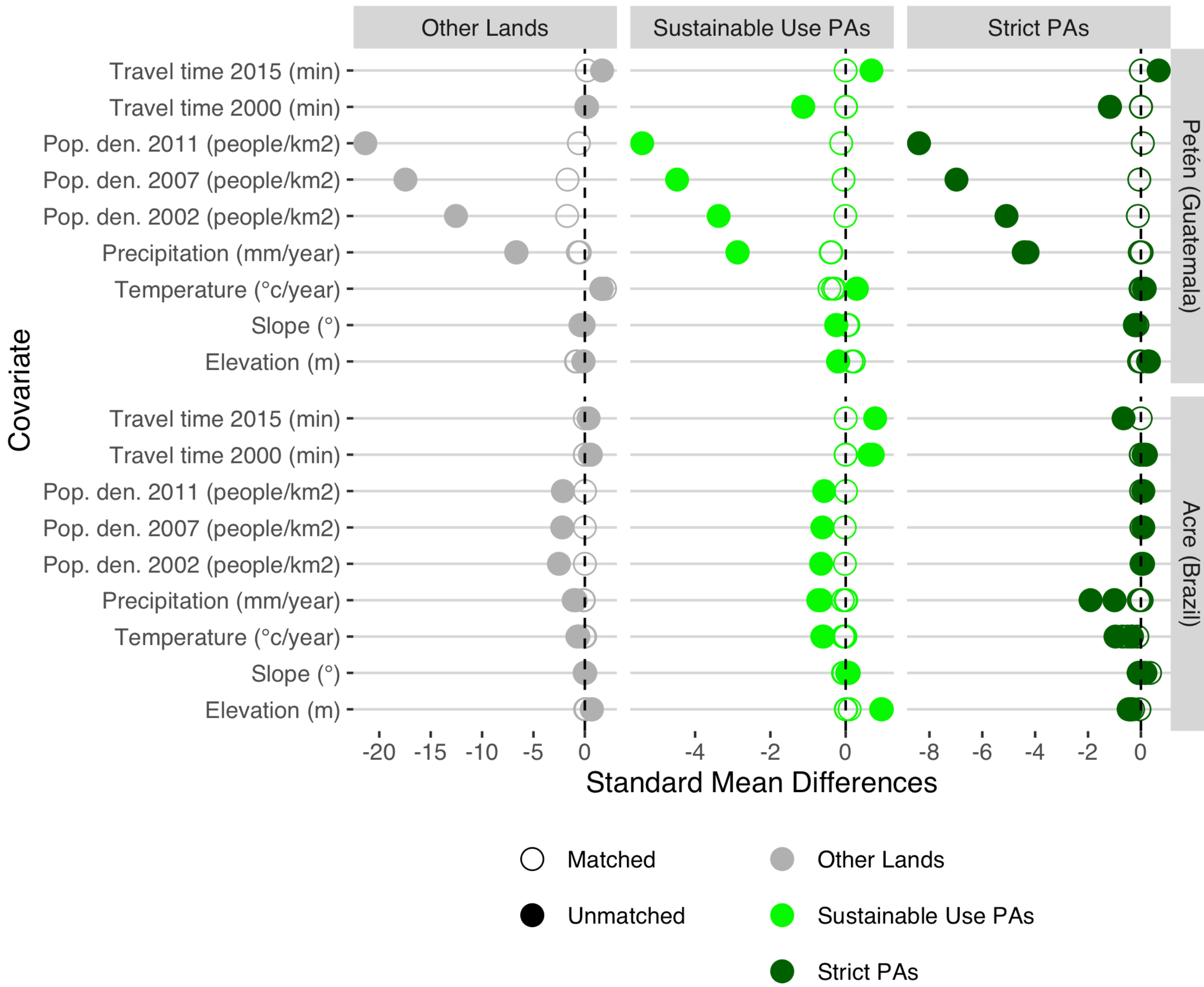

Figure 2. Covariates standard mean differences between Community Managed PAs and Other Lands, Sustainable Use PAs, and Strict PAs before (Unmatched) and after matching analysis (Matched) in the Petén (Guatemala) and Acre (Brazil).

Temporal effects on carbon stocks and avoided carbon emissions

To control the influence of spatial location and estimate the effectiveness of Community Managed PAs on carbon stocks dynamics, we used matching analysis and linear mixed models in three periods of time: 2003-2007, 2007-2011, and 2011-2015 (Figure 2, Supplementary Material, Figure S1). First, we estimated the temporal effects of Community Managed PAs on annual carbon stocks (Figure 3). These effects describe the annual mean difference of carbon stocks between Community Managed PAs and different land tenures. The temporal effects in 2007, 2011, and 2015 show that Community Managed PAs stored significantly different carbon stocks ($p < 0.05$) compared with Other Lands, Sustainable Use PAs, and Strict PAs. During 2007 Petén's Community Managed PAs stored around ~130% (44 tC/ha) more carbon stocks than Other Lands. This effect was moderate with Sustainable Use PAs (~15%: 8 tC/ha), and Strict PAs (~5%; 2 tC/ha). In 2011, these spatial effects increased over all land tenures, but only increased over Strict PAs during 2015 (9.4%; 6.5 tC/ha). Translated into Effects Ratios, Community Managed PAs in Petén were between 29 and 1.75 times more likely to store higher carbon stocks than Other Lands and Strict PAs in 2015, respectively (Figure 4). According to sensitivity analyses, these temporal Effects Ratios could be explained away by unmeasured covariates with Effects Ratios (i.e., E-Values) ranging 50 (Other Lands) and 2.8 (Strict PAs), but weaker unmeasured covariates could not do so. Hence, Community Managed PAs' effects on carbon stocks were robust across different land tenures in Petén.

Compared to Petén, the effects of Community Managed PAs were milder in Acre, and the highest difference on carbon stocks in 2007 occurred with Other Lands (9.3 %; 10 tC/ha) followed by Sustainable Use PAs (6.8%; 8 tC/ha). After 2011, these effects reduced below 2% (i.e., 4.2 tC/ha in Other Lands and 3.9 tC/ha in Sustainable Use PAs), resulting in less robust effects that were more likely to be changed by unobserved covariates (Effects Ratios = 1.08, E-Values = 1.38). Conversely, Community Managed PAs in Acre stored 2.3% (- 4 tC/ha) less carbon than Strict PAs, but this effect increased in 2011 (-1.26%; - 2tC/ha) and 2015 (-1%; -1.5 tC/ha). These findings suggest that Community Managed PAs in both jurisdictions maintained higher carbon stocks than the other land tenures throughout 2007, 2011 and 2015, except when compared to Strict PAs in Acre. Moreover, Petén's Community Managed PAs have increased their effect on carbon stocks, whereas Acre's tended to reduce theirs.

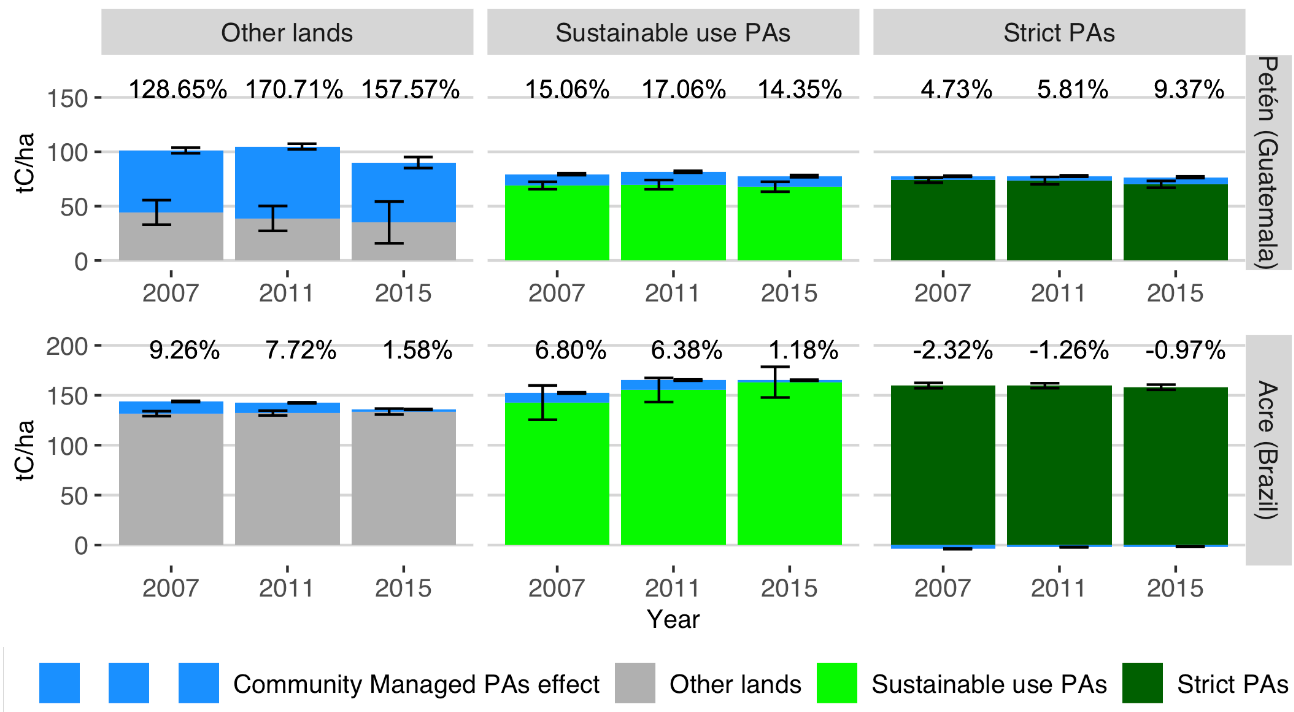

Figure 3. The temporal effects of Community Managed PAs on carbon stocks in Petén (Guatemala) and Acre (Brazil). Significant ($p < 0.05$) temporal effects are represented as blue bars and percentages, indicating the additional/fewer carbon stocks secured by Community Managed PAs relative to the carbon stocks baselines of Other Lands (grey), Sustainable Use PAs (light green), and Strict PAs ITs (dark green). Error bars indicate 95% confidence intervals for the baselines and temporal effects.

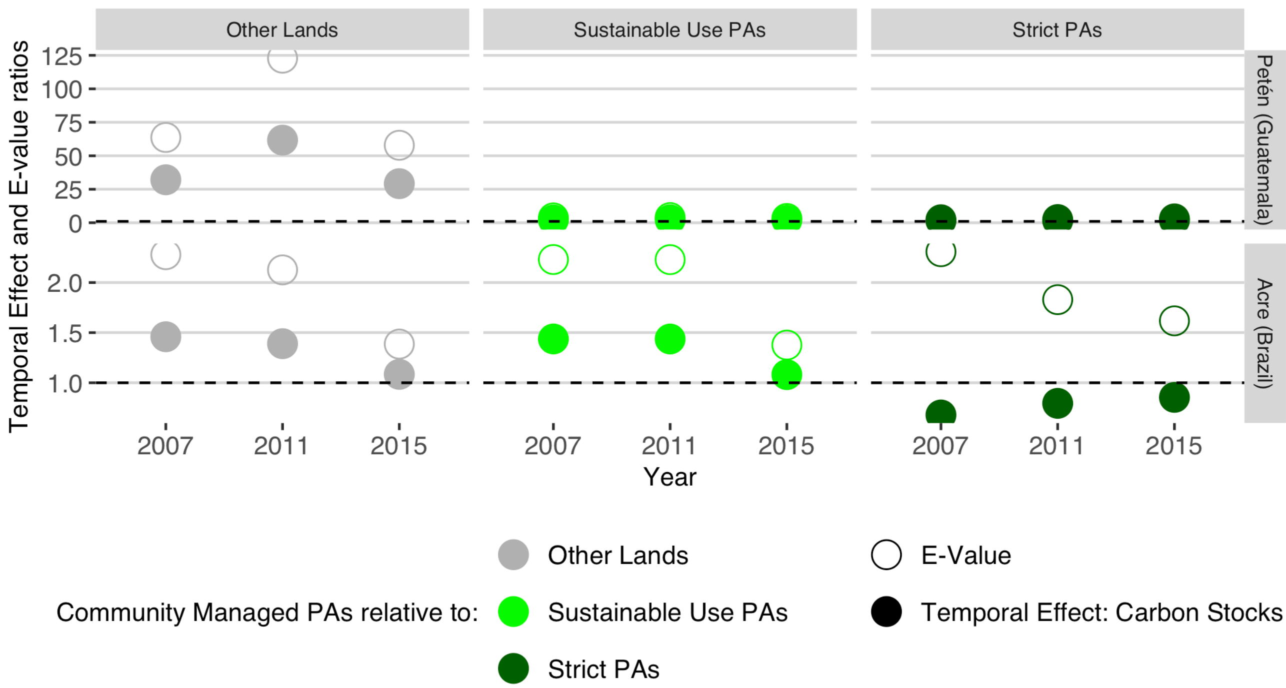

Figure 4. Sensitivity analysis in the temporal effects of Community Managed PAs on carbon stocks in Petén (Guatemala) and Acre (Brazil). The temporal effect ratio (unitless) is equivalent to the probability of a positive temporal effect in the treatment (i.e., Community Managed PAs) divided by the probability of a positive temporal effect in the controls (i.e., Other Lands, Sustainable Use PAs, and Strict PAs). The E-value represents the minimum strength that an unmeasured covariate would need to have with the treatment and the temporal effect for the treatments and temporal effect association not to be causal.

In addition to estimating Community Managed PAs temporal effects on carbon stocks, we estimated their temporal effects on avoided CO2 equivalent emissions (Figure 5). These effects derive from the differences in carbon stock changes between Community Managed PAs and different land tenures in the periods 2003-2007, 2007-2011, and 2011-2015. After controlling for covariates, the results exhibit that Community Managed PAs in Petén and Acre have a significant net effect on avoided carbon emissions ($p < 0.05$). For Petén, Community Managed PAs avoided more carbon emissions than Other Lands (~ 47 tCO2-eq/ha), Sustainable Use PAs (9.3 tCO2-eq/ha) and Strict PAs (4.3

tCO2-eq/ha) throughout the period 2003-2007. In the period 2007-2011, these effects reduced more than half relative to Other Lands (~19 tCO2-eq/ha) and Strict PAs (1.59 tCO2-eq/ha). Further reductions in 2011-2015 resulted in effects that ranged between 4.6 tCO2-eq/ha (Other Lands) and 1.95 tCO2-eq/ha (Strict PAs). When translated into Effects Ratios (Figure 6), Petén's Community Managed PAs were 3.4 times more likely to avoid carbon emissions than Other Lands in the period 2003-2007. To explain away these effects, unobserved covariates would have required effect ratios (i.e., E-value) of at least 5.85. In this case, the Effects Ratio and E-values in the period 2011-2015 reduced to 1.3 and 1.92, respectively. Similarly, the temporal effects over Sustainable Use and Strict PAs in Petén were slightly less robust (Effects Ratios of 1.17 and 1.33, respectively) to unobserved covariates (E-values of 1.90 and 1.5, respectively) in the period 2011-2015. These findings imply that reductions in avoided carbon emissions result in less robust effects to unobserved covariates.

As Community Managed PAs in Petén, their effects in Acre were significant on avoided carbon emissions (Figure 5). Between 2003 and 2007, Community Managed PAs in Acre resulted in net avoided emissions compared to Other Lands (8 tCO2-eq/ha), Sustainable Use PAs (7.2 tCO2-eq), and Strict PAs (1.7 tCO2-eq). Except for Strict PAs (1.8 tCO2-eq/ha), these effects decreased in relation to Other Lands (3.2 tCO2-eq/ha) and Sustainable Use PAs (5.8 tCO2-eq/ha) during 2007-2011. The same comparison between 2011 and 2015 resulted in further decreases. Community Managed PAs from Acre avoided emissions of 2.15 tCO2-eq/ha (Other Lands), 3.75 tCO2-eq/ha (Sustainable Use PAs), and 0.98 tCO2-eq/ha (Strict PAs). Expectedly, a reduction in avoided carbon emissions results in less robust effects that could be explained away by unobserved covariates (Figure 6). For example, Community Managed PAs were 1.18 times more likely to avoid carbon emissions than Other Lands in 2003-2007, and only an effect on unobserved covariates of 1.6 (i.e., E-value) or higher could explain away this association. During 2011 and 2015, those values dropped to an Effects Ratio of 1.08 and E-Value of 1.35. These temporal effects indicate that Community Managed PAs in Petén and Acre conserved carbon stocks by avoiding more carbon emissions than Other Lands, Sustainable Use PAs, and Strict PAs. Moreover, these effects and their robustness towards unobserved covariates tended to reduce throughout 2007-2011 and 2011-2015. Nevertheless, the reduced effects of Community Managed PAs seem to be driven by a reduction in carbon emissions throughout Other Lands, Sustainable Use PAs, and Strict PAs (Supplementary Material, Figure S2).

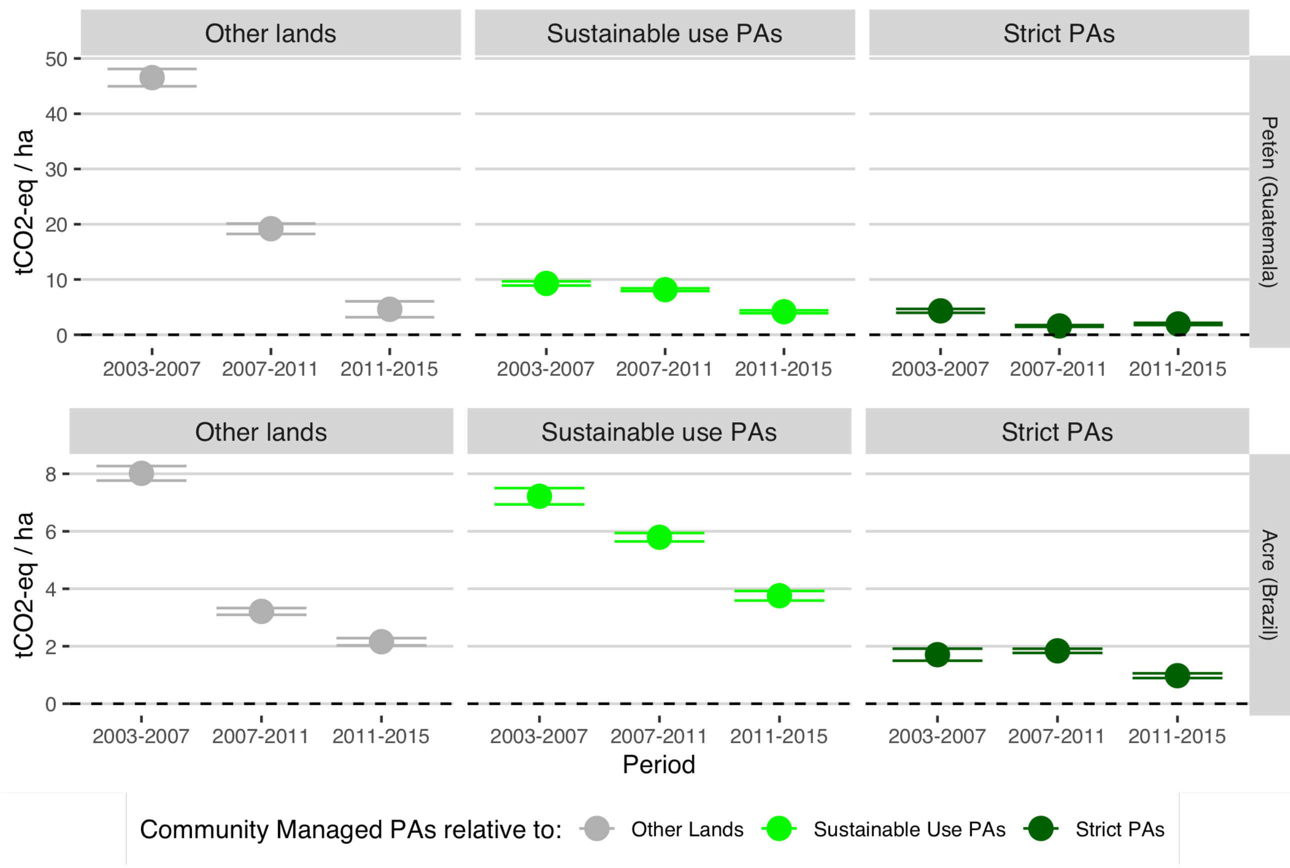

Figure 5. The temporal effects of Community Managed PAs on avoided carbon emissions in Petén (Guatemala) and Acre (Brazil). Positive temporal effects ($p < 0.05$) indicate net avoided carbon emissions relative to Other Lands (grey), Sustainable Use PAs (light green), and Strict PAs ITs (dark green). Error bars indicate 95% confidence intervals for temporal effects.

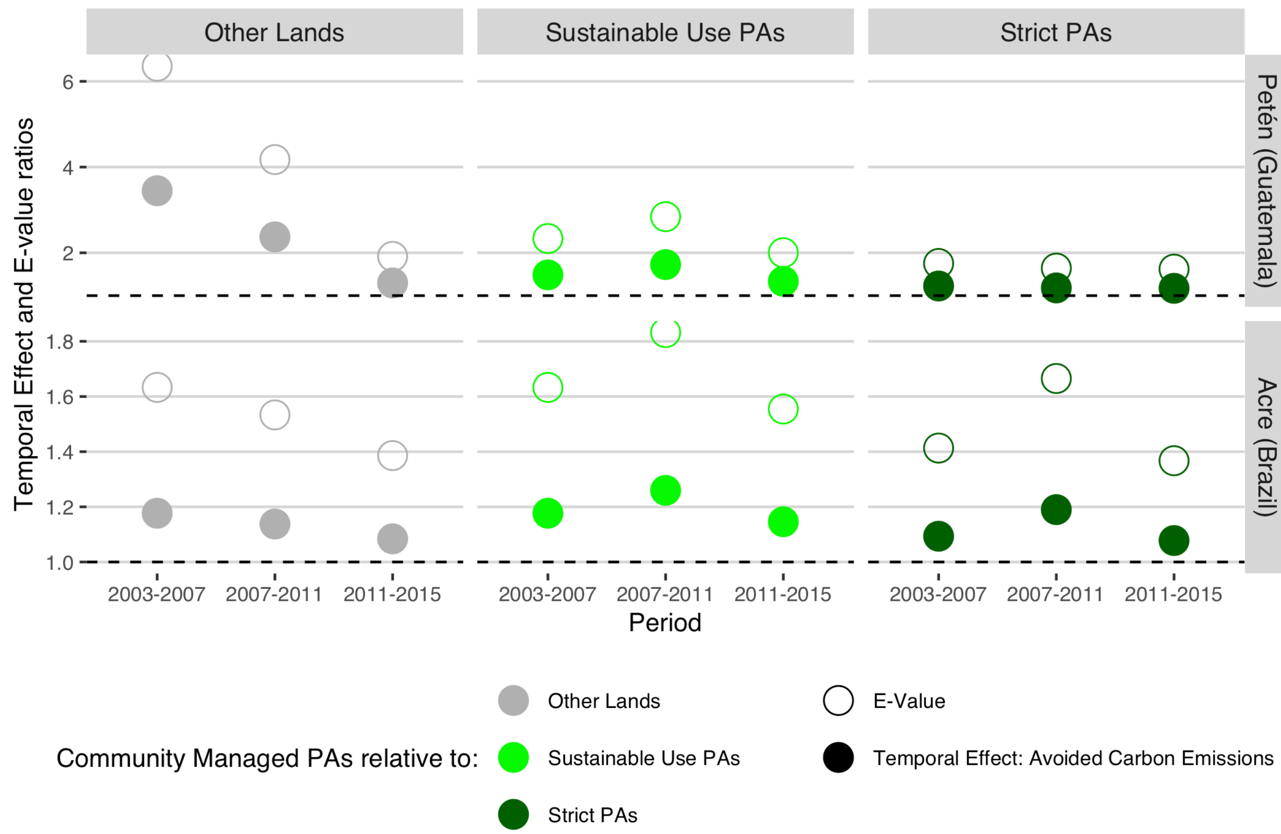

Figure 6. Sensitivity analysis in the temporal effects of Community Managed PAs on avoided carbon emissions in Petén (Guatemala) and Acre (Brazil). The temporal effect ratio (unitless) is equivalent to the probability of a positive temporal effect in the treatment (i.e., Community Managed PAs) divided by the probability of a positive temporal effect in the controls (i.e., Other Lands, Sustainable Use PAs, and Strict PAs). The E-value represents the minimum strength that an unmeasured covariate would need to have with the treatment and the temporal effect for the treatments and temporal effect association not to be causal.

Spatial effects on carbon stocks and avoided emissions

We further assessed the effectiveness of Community Managed PAs by exploring their carbon stocks and avoided emissions relative to their surroundings after controlling for spatial location (Supplementary Material, Figures S3, S4, S5) through geographic discontinuity designs. Specifically, these spatial effects compared the carbon stocks and avoided emissions inside and outside Community Managed PAs' at 1 km, 5km, 10km, and 15km from their boundaries in the years and periods aforementioned. Overall, both jurisdictions display spatial effects on carbon stocks that partially resemble the temporal effects, where Community Managed PAs effectiveness is more evident over Other Lands and Sustainable Use PAs. However, each jurisdiction corresponds to specific geographical settings.

Regarding Petén, Community Managed PAs do not share boundaries with Other Lands and are embedded inside the Maya Biosphere Reserve (Figure 1). When compared to neighboring Sustainable Use PAs in 2007, Community Managed PAs stored additional carbon stocks between 1.5% (1.2 tC/ha) at 1km and ~12% at 15km (8.3 tC/ha) and therefore Effects Ratios between 1.2 and 1.8-fold, respectively (Figures 2F, 2G). Instead, Community Managed PAs in Petén only stored significantly higher carbon stocks than surrounding Strict PAs at 10 km (~ 4.2%; 3 tC/ha) and 15 km (8.1%; 5.8 tC/ha) from their boundaries in 2007, which translate in Effects Ratios of 1.4 and 1.8, respectively. These results imply that Community Managed PAs were ~1.8 times more likely to store higher carbon stocks than Sustainable Use PAs and Strict PAs at 15 km in 2007, requiring unobserved covariates with Effects Ratios (i.e., E-values) larger than 3 to explain away this association. In both comparisons, the spatial effects increased in 2011, ranging between 0.5% and 2.4%. In 2015, there were slight variations (-4%; 7%) in the spatial effects that usually resulted in larger effects than in 2007. Thus, Community Managed PAs in Petén maintained higher and more stable carbon stocks than their surroundings until 2015 (Supplementary Material, Figure S6).

Acre's Community Managed PAs, which did not share boundaries with Strict PAs in 2003, had significant effects over Other Lands and Sustainable Use PAs that also increased with distance (some Strict PAs were founded after 2003 but were included after 2007 in this analysis) (Figure 7). For instance, these areas stored significantly higher carbon stocks than Other Lands with effects that ranged between 5.6% at 1km (7 tC/ha) and 15.3% at 15 km (20 tC/ha) in 2007. However, Community Managed PAs effects over Other Lands and Sustainable Use PAs in Acre decreased and resulted in effects below 10 tC/ha at 15km in 2015. In other words, Community Managed PAs in 2007 were around 1.6 and 2 times more likely to store higher carbon stocks than Sustainable Use PAs and Other Lands at 15 km (E-values 2.4-3.2) (Figure 8). However, these Effects Ratios dropped to ~1.3 in 2015, becoming less robust to unobserved covariates (E-values < 1.9). Contrasting Petén, Community Managed PAs' effect in Acre was not significantly different from Strict PAs at 1km and 15 km and was significantly lower at 5 km and 10 km in 2007 and 2015. Given the relative stability of carbon stocks in surrounding land tenures (Supplementary Material, Figure S7), the reducing spatial effects on carbon stocks in Acre seem to be driven by Community Managed PAs. Consequently, except for Strict PAs in Acre, Community Managed PAs tended to store higher carbon stocks than surrounding land tenures. This effect increased and became more robust to unobserved covariates with the distance to boundaries. However, Petén's Community Managed PAs spatial effects remained relatively stable when compared to surrounding lands throughout 2011 and 2015, whereas Acre's resulted less effective during the same period.

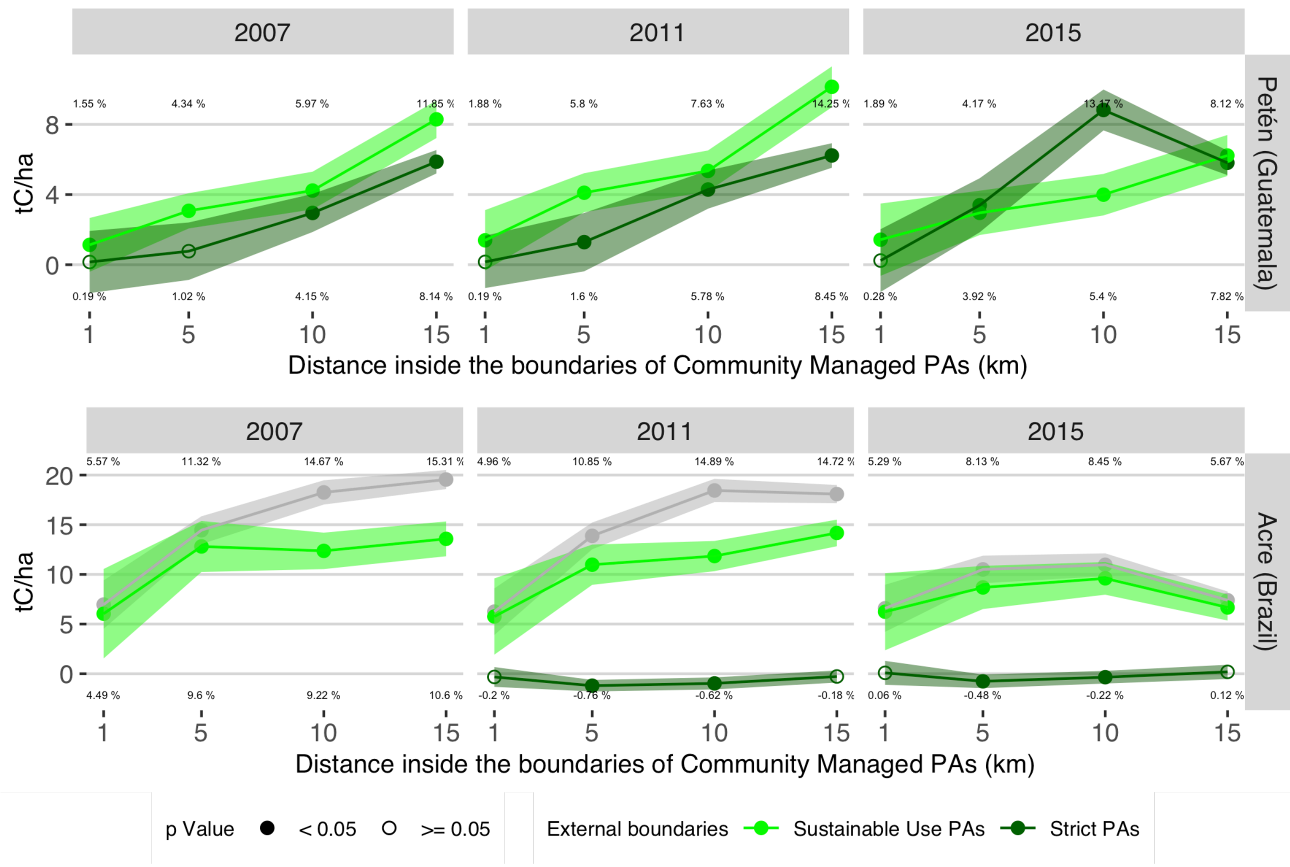

Figure 7. The spatial effects of Community Managed PAs on carbon stocks during 2007, 2011, and 2015 in Petén (Guatemala) and Acre (Brazil). The points and percentages are the spatial effects, indicating the additional/fewer carbon stocks secured inside the boundaries of Community Managed PAs relative to Other Lands (gray), Sustainable Use PAs (light green), and Strict PAs (dark green).

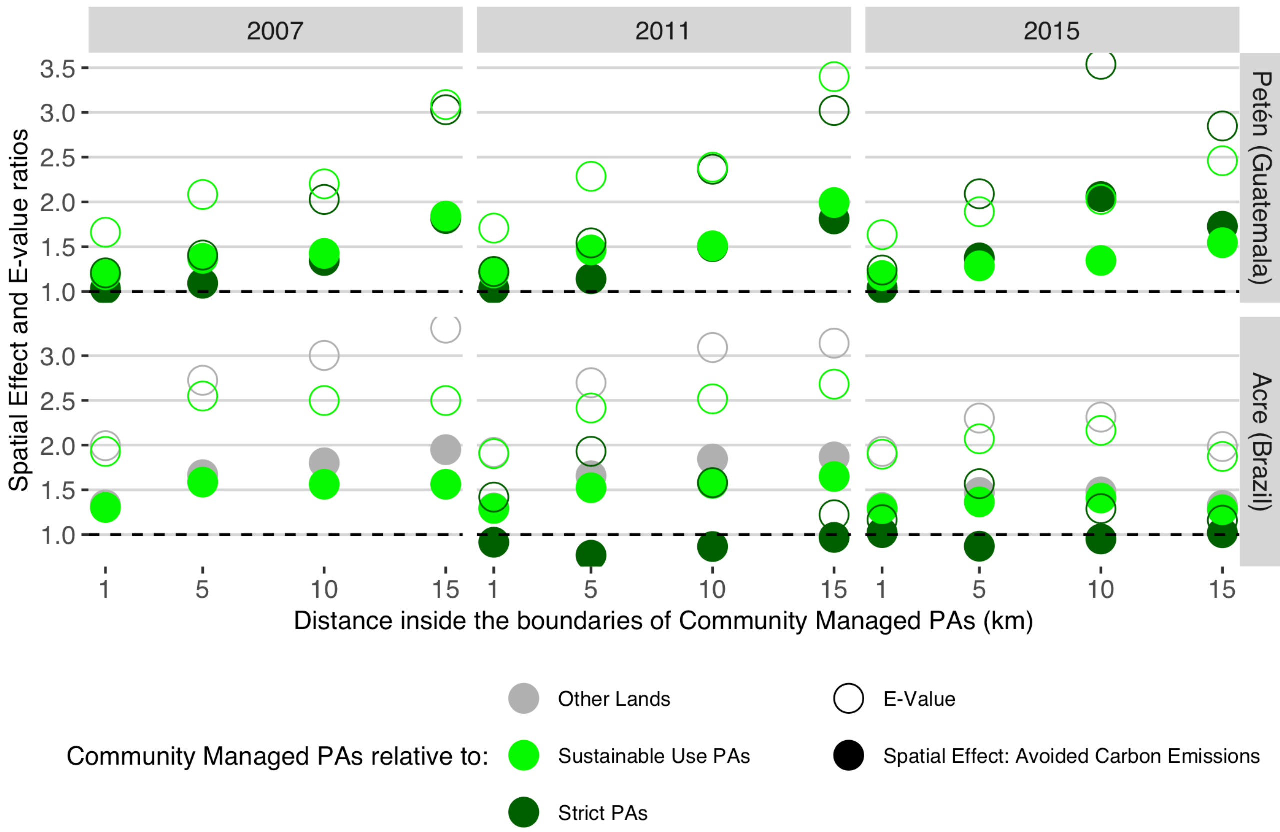

Figure 8. Sensitivity analysis in the spatial effects of Community Managed PAs on carbon stocks in Petén (Guatemala) and Acre (Brazil). The temporal effect ratio (unitless) is equivalent to the probability of a positive temporal effect in the treatment (i.e., Community Managed PAs) divided by the probability of a positive temporal effect in the controls (i.e., Other Lands, Sustainable Use PAs, and Strict PAs). The E-value represents the minimum strength that an unmeasured covariate would need to have with the treatment and the spatial effect for the treatments and spatial effect association not to be causal.

Community Managed PAs' spatial effects on avoided emissions partially explain the changing effects on carbon stocks in Petén and Acre (Fig 2H). The spatial patterns of avoided emissions in Petén resemble those on carbon stocks. Compared to surrounding Sustainable Use PAs and Strict PAs in the 2003-2007 time period, Community Managed PAs did not significantly avoid more emissions at 1km but had significant effects at 10 and 15 km from their boundaries. For instance, Community Managed PAs avoided around 7.8 (Strict PAs) and 4.1 tCO2-eq/ha (Sustainable Use PAs) at 15 km. During 2007-2011, Community Managed PAs resulted in more avoided emissions than Sustainable Use PAs, resulting in 1 tCO2-eq/ha at 1km and 8.1 tCO2-eq/ha at 15 km from their boundaries. Relative to Strict PAs, these effects were more moderate in the same period (< 2 tCO2-eq/ha). Finally, in 2011-2015, the net avoided emissions inside Community Managed PAs boundaries had a wider range relative to Sustainable Use PAs (1-9 tCO2-eq/ha) and increased relative to Strict PAs (1-3.8 tCO2-eq/ha). These spatio-temporal changes in avoided emissions are reflected in stable or even increasing robustness of the effects towards unobserved covariates (Figure 10). In other words, Community Managed PAs' boundaries have robust effects that increased avoided emissions until 2015.

Regarding Acre, the avoided carbon emissions did not necessarily increase within the distance to boundaries. Relative to Other Lands, Community Managed PAs only avoided emissions at 10 km (4.4 tCO2-eq/ha) and 15 km (6.6 tCO2-eq/ha) from their boundaries in the period 2003-2007. These effects subsequently reduced in 2007-2011, and in 2011-2015 resulted in no significant differences in avoided emissions with Other Lands. Compared to surrounding Sustainable Use PAs, the avoided emissions oscillated throughout the three-time periods. During 2003-2007, Community Managed PAs at 1 and 15km avoided around ~ 0-7.6 tCO2-eq/ha, 4.2-5.3 tCO2-eq/h in the subsequent period, and 5-8.2 tCO2-eq/h in 2011-2015. Community Managed PAs in Acre avoided more carbon emissions than surrounding Strict PAs in 2007-2011 (> 1.3 tCO2-eq/h) and 2011-2015 (> 0.7 tCO2-eq/h) at 5 and 10 km from their boundaries, but these effects were the least robust to unobserved covariates in 2011-2015 (e.g., Effects Ratio = 1.07 and E-Value = 1.12 at 5 km). Overall, these results indicate that in both jurisdictions, Community Managed PAs are more effective in avoiding carbon emissions than neighboring Sustainable Use PAs, and Strict PAs, to a lower extent. According to the spatial effects on carbon stocks and avoided emissions, the effectiveness of Community Managed PAs' boundaries exhibit differences across jurisdictions. In Petén, as the distance to Community Managed PAs boundaries increase, more emissions are avoided inside, resulting in additional carbon stocks, and usually, more robust effects to unobserved covariates from 2003 until 2015. The results in Acre indicate that Community Managed PA's boundaries have become less effective in avoiding emissions, which translates into reduced carbon stocks, and spatial effects that are more prone to the influence of unobserved covariates.

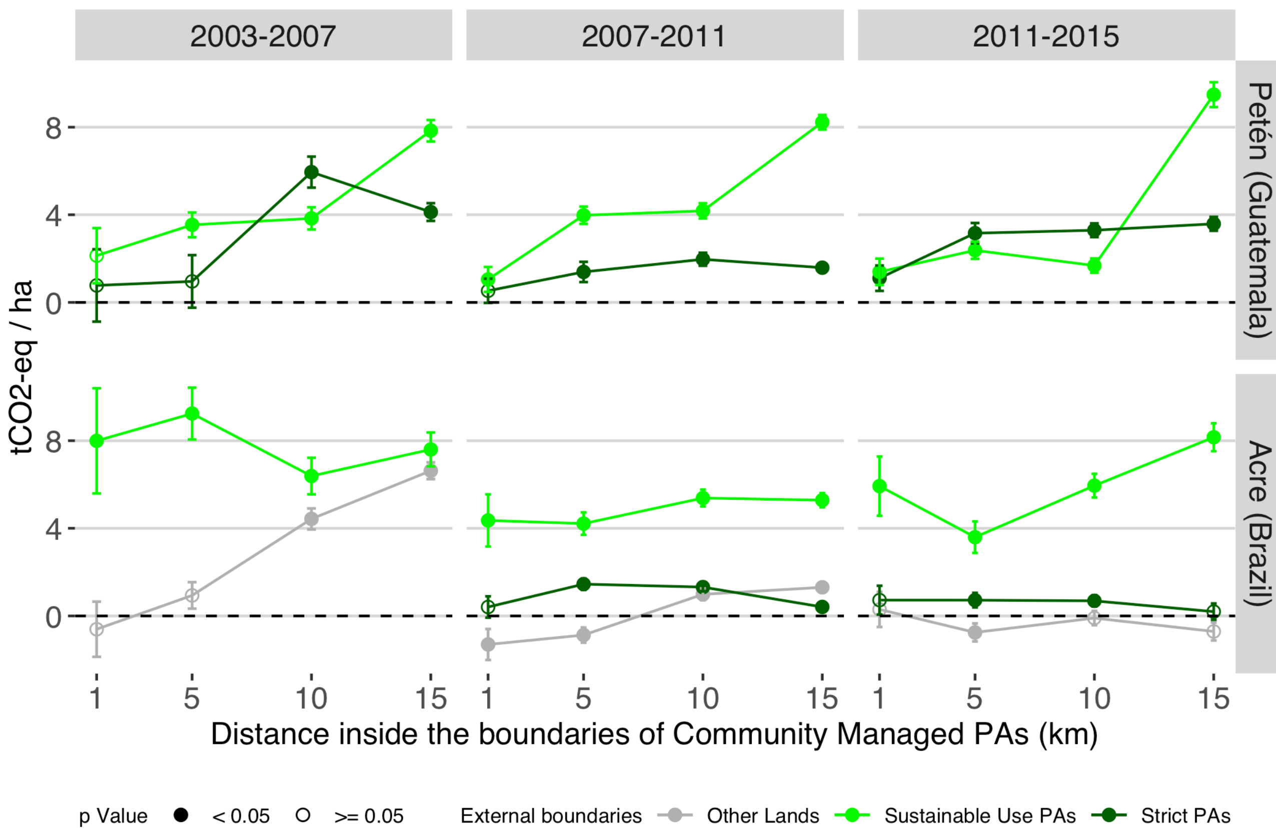

Figure 9. The spatial effects of Community Managed PAs on avoided carbon emissions in Petén (Guatemala) and Acre (Brazil). Positive temporal effects indicate net avoided carbon emissions relative to Other Lands (grey), Sustainable Use PAs (light green), and Strict PAs (dark green). Error bars indicate 95% confidence intervals for temporal effects.

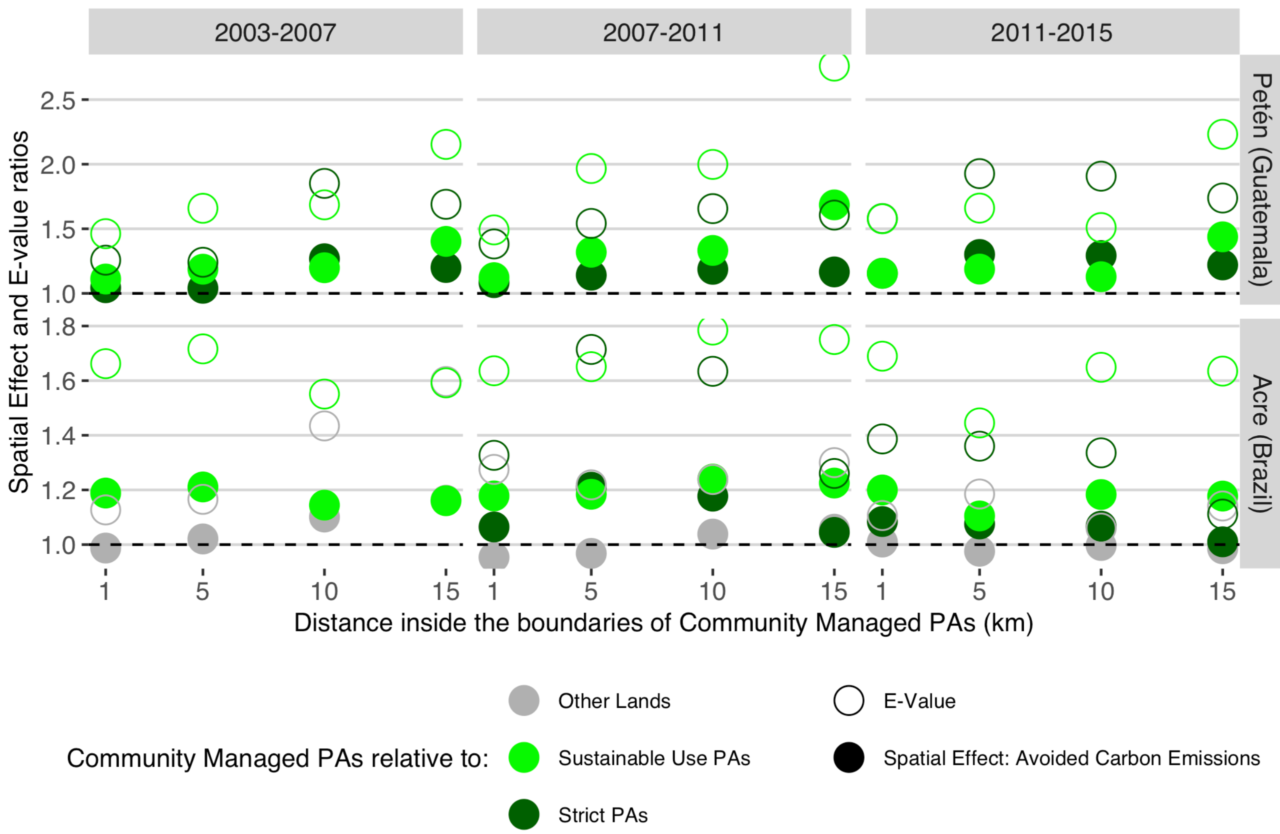

Figure 10. Sensitivity analysis in the spatial effects of Community Managed PAs on avoided carbon emissions in Petén (Guatemala) and Acre (Brazil). The temporal effect ratio (unitless) is equivalent to the probability of a positive temporal effect in the treatment (i.e., Community Managed PAs) divided by the probability of a positive temporal effect in the controls (i.e., Other Lands, Sustainable Use PAs, and Strict PAs). The E-value represents the minimum strength that an unmeasured covariate would need to have with the treatment and the spatial effect for the treatments and spatial effect association not to be causal.

Discussion

Our study estimates Community Managed PAs' effect on carbon stocks and avoided carbon emissions in the Department of Petén (Guatemala) and the state of Acre (Brazil). Particularly, we focus on the temporal and spatial effects of Community Concessions in Petén and Extractive Reserves in Acre, relative to Other Lands (i.e., unprotected), other Sustainable Use PAs, and Strict PAs using matching methods and geographic discontinuity designs. Our results highlight that Community Managed PAs not only differ from Other Lands in market access and agriculture suitability but also differ with Sustainable Use PAs (i.e., IUCN V-VI or equivalent) and Strict PAs (i.e., IUCN I-IV). After controlling for these spatial covariates, the results indicate that Community Managed PAs in Petén and Acre effectively maintain carbon stocks and avoid carbon emissions.

The effectiveness of Community Managed PAs

The effectiveness of Community Managed PAs on carbon stocks dynamics varied across jurisdictions and land tenures used as counterfactuals. Overall, our results are consistent with earlier studies highlighting the effectiveness of PAs that allow non-industrial extractive activities over Other Lands that lack protection. Compared to Other Lands, and not comparing PAs directly, Nelson & Chomitz (2011) show that Sustainable Use PAs result in lower fire incidence than Strict PAs across Latin America and the Caribbean. This indirect comparison has also established the effectiveness of Community Managed PAs on avoided deforestation (i.e., Community Concessions) in Petén (Blackman 2015). Our results are consistent with these findings and additionally established that current Community Concessions in Petén are more effective than Sustainable Use PAs and Strict PAs in conserving carbon stocks and avoiding carbon emissions. That is, National Parks, Multiple Use Zones in the Maya Biosphere Reserve (e.g., Cooperatives, revoked concessions) and PAs with IUCN category V-VI across Petén. Similar to Pfaff et al. (2014) and Koskimäki et al. (2021), our results also established that Community Managed PAs (i.e., Extractive Reserves) in Acre (Brazil) have a significant role in forest conservation. Further direct comparisons with multiple land tenures in our study indicate that the greatest impacts of Extractive Reserves on carbon stocks dynamics occur over Other Lands, followed by Sustainable Use PAs (e.g., National Forests, State Forests, Settlements in public forests). Extractive Reserves in Acre were also more effective than Strict PAs in avoiding carbon emissions, but slightly less effective in storing carbon stocks, and not consistently different from Strict PAs in their vicinity.

However, our results are not consistent with studies that directly compare different categories of PAs. For example, Elleason et al. (2021) found that across the neotropics, Strict PAs have lower deforestation than other PAs. Similarly, Strict PAs in Indonesia, Thailand, and to a limited extent in Bolivia and Costa Rica, result in higher avoided deforestation when they are directly compared to Sustainable Use PAs (Ferraro et al. 2013). This lack of consistency might be explained by two factors in our study design. First, our study is more similar to Andam et al. (2013), which compare Sustainable Use PAs to Other Lands and Strict PAs in terms of avoided deforestation and additional regrowth. By using annual carbon stocks and avoided carbon emissions as outcome variables, our study design provides an integral assessment on Community Managed PAs, reflecting their effectiveness on avoided deforestation, and additionally, on avoided degradation and recovery. Furthermore, regardless of the relative effectiveness of Strict PAs over less strict PAs (here, Sustainable Use and Community Managed PAs), the differences tend to be modest and even statistically insignificant in previous studies and in our own findings. Thus, our results exhibit that Community Managed PAs in Petén and Acre are more effective than Other Lands and Sustainable Use PAs, and at least as effective as Strict PAs, in preserving carbon stocks and avoiding emissions.

Jurisdictional and local land-use dynamics

Despite the effectiveness over different land tenures, Community Managed PAs in Petén and Acre exhibit an overall reduction in their capacity to avoid carbon emissions. This reduced capacity does not necessarily imply increasing carbon losses in Community Managed PAs. After controlling for covariates, our results suggest that Other Lands, Sustainable Use PAs, and Strict PAs have reduced and stabilized their carbon emissions, causing more moderate net avoided emissions on Community Managed PAs. Jurisdictional land-use dynamics may explain these reducing spatial effects. Across Petén, extending forests fires and deforestation have been reported since the 1980s (Radachowsky et al. 2012; Bray et al. 2008), and they seem to have increased in the 2000s, followed by a reduction in the early 2010s (Hodgdon et al. 2015; Bullock et al. 2020; Global Forest Watch 2021). This temporal pattern coincides with the large expansion of oil palm in southern Petén during the 2000s that partially dropped in the 2010s (Hervas 2021). In Acre, deforestation reached a peak in the early 2000s and then reduced throughout the 2000s and early 2010s (INPE 2020). The reduction of deforestation in the Brazilian Amazon seems in part explained due to a reduced pressure on old forest frontiers with consolidated rural areas, which corresponds to the northern part of Acre (Schielein and Börner 2018). Consequently, the reduced effectiveness of Community Managed PAs on avoided carbon emissions in Petén and Acre partially correspond to a jurisdictional-wide reduction in land-use pressure over forests.

The spatial effects reflect some local land-use dynamics that are not evident in the temporal effects. Petén's Community Managed PAs boundaries have maintained larger carbon stocks and avoid more emissions compared to neighboring Sustainable Use PAs and Strict PAs between 2003 and 2015. According to Devine et al. (2020), Laguna del Tigre National Park (Strict PA) and Multiple Use Zones (Sustainable Use PAs) that share boundaries with some Community Managed PAs have been subject to forest clearing, land speculation, and land grabbing. Acre's Community Managed PAs between 2007 and 2015 reduced their effect on carbon stocks and avoided emissions, which contrasts with relatively stable carbon dynamics in Other Lands and Sustainable Use PAs in their vicinity. This reduced effectiveness is directly attributable to Community Managed PAs and might be explained by the diversification of income activities. Traditionally, households in Acre's Community Managed PAs relied on the extraction of natural rubber (H. brasiliensis) and Brazil nut (B. excelsa) but have recently incorporated cattle ranching (Duchelle et al. 2014; Maciel et al. 2018; Kröger 2020), potentially increasing carbon emissions and reducing carbon stocks. Our results highlight the need for temporal and spatial effects for integral assessments. While the temporal effects may exhibit overall land-use dynamics across a jurisdiction, the spatial effects evidence local land-use pressures emerging inside or around the boundaries of Community Managed PAs.

Community Managed PAs and REDD+

In Petén and Acre, Community Managed PAs' effects on carbon stocks dynamics can also be interpreted in the context of governance and REDD+. ACOFOP, which associates Community Concessions in Petén, became a bridging social organization that has facilitated support relations with NGOs, certification programs, and government agencies (Taylor 2012; Butler and Current 2021). These support relations have resulted in a governance system with transparent management plans, wide local representation, and diversified forest activities that include timber, non-timber forest products, and in some cases, tourism (Millner et al. 2020). Regarding Acre, the rubber tappers organization has redefined itself as one of extractive populations after years of articulation with diverse social organizations from the Brazilian Amazon (Gomes et al. 2018). This bridging social organization became a platform to actively participate in State and Federal policies, especially between the 1990s and 2000s, resulting in the increase of Extractive Reserves and securing subsistence activities of forest extractivists households that are required to maintain 90% of forest cover from their landholdings (Gomes et al. 2018). We infer from our results that these bridging social organizations have a major role in carbon stock dynamics and drive Community Managed PAs' governance systems in Petén and Acre.

These dynamic governance systems have contributed to the creation of GuateCarbon in Petén (Hodgdon et al. 2013) and SISA in Acre (Rosa Da Conceição and Börner 2020), which exhibit two different REDD+ models. GuateCarbon is a local REDD+ program aiming to generate carbon credits in voluntary markets (Hodgdon et al. 2013). SISA is a jurisdictional initiative that includes multiple environmental policies, including a REDD+ program (ISA-Carbono) that integrates international funding bodies, a recipient state (Acre), and multiple local stakeholders (Sills et al. 2014; Sunderlin et al. 2015). Using multiple (i.e., Other Lands, Sustainable Use PAs, and Strict PAs) and conservative baselines (i.e., controlling for agricultural suitability and market access), our results indicate that Community Managed PAs in Petén and Acre were effective in avoiding emissions from deforestation and degradation before and after these initiatives began to operate.

However, according to our results, Community Managed PAs net avoided emissions reduced after GuateCarbon and SISA began to operate, questioning the additionality of these REDD+ projects. As explained above, there was an overall reduction in avoided emissions outside Community Managed PAs in Petén and Acre. Moreover, it is worth noting that our results are not meant to coincide with the baselines or emissions targets established by GuateCarbon or ISA-Carbono. Estimating temporal and spatial effects through matching analysis and geographic discontinuity designs provide conservative estimates that tend to exclude core areas with the most stable and higher carbon stocks (Alejo et al. 2021). In fact, before controlling for market access and agriculture suitability covariates, Community Concessions in Petén displayed an increase in carbon stocks after GuateCarbon began. Similarly, carbon stocks in Extractive Reserves from Acre have remained stable since 2003. In Acre, SISA has maintained previous initiatives that benefited communities in Extractive Reserves, such as the rubber-tapper subsidy program (Rosa Da Conceição and Börner 2020), and implemented others with small colonist farmers and cattle ranchers (Sills et al. 2014). Our results suggest that SISA may have partially influenced an overall reduction in land-use emissions in Acre. Considering that ISA-Carbono remains in the initial stages of implementation (Rosa Da Conceição and Börner 2020), it is early to establish the additionality of this REDD+ project. Hence, our results highlight that forest communities with bridging social organizations supported by government institutions and international organizations (e.g., NGOs, international aid) may contribute to climate change mitigation and forest conservation targets, like those envisioned by GuateCarbon and SISA. Finally, we also identified that Community Managed PAs conserve considerable amounts of carbon stocks. While the conservation and enhancement of carbon stocks have not been clarified by the UNFCCC, our results also highlight the need to include these activities in REDD+'s portfolio (Funk et al. 2019).

Study limitations

While we consider that this study offers an integral assessment of Community Managed PAs on carbon stocks dynamics, four limitations should be noted. First, Community Managed PAs represent a diverse group of forest communities with particular land-use dynamics. Previous studies have shown the differences among past-resident, new-resident, and non-resident Community Concessions in Petén (Radachowsky et al. 2012; Blackman 2015; Taylor 2012). Our study focuses on those concessions that remained active and certified, mostly past-resident and non-resident communities, that became proponents of the REDD+ program GuateCarbon (Hodgdon et al. 2013). Second, our study does not distinguish carbon emissions from deforestation and degradation. According to Bullock et al. (2020), deforestation is more prevalent than degradation in Petén. Oppositely, carbon emissions in PAs from the Brazilian Amazon are dominated by degradation (Kruid et al. 2021). Future quasi-experimental studies controlling for spatial location covariates may benefit from distinguishing the role of deforestation and degradation in Community Managed PAs. Third, our study assesses Community Managed PAs in terms of an ecological indicator (i.e., carbon stocks). Other studies also explore the role of PAs in terms of poverty, income, and livelihoods (e.g., Bocci et al., 2018; Duchelle et al., 2014; Miranda et al., 2016). In addition to these indicators of ecological and social 'success', Community Managed PAs need to be evaluated in terms of tenure security (Robinson et al. 2014) and participation across genders, classes, and ethnicity (Millner et al. 2020). Fourth, the time frame of our study does not cover the last five years that display an upturn in deforestation and forest degradation in Guatemala and Brazil (Bullock et al. 2020; Kruid et al. 2021), which could deeply influence the role of Community Managed PAs in climate change mitigation.

Conclusions

Community Managed PAs represent a unique form of forest governance, as they aim to reconcile conservation, climate change mitigation, and local livelihoods. Our study expanded the methodological scope of previous studies and assessed the role of Community Managed PAs on carbon dynamics relative to different land tenures. Using both temporal and spatial assessments, we found that Community Concessions in Petén (Guatemala) and Extractive Reserves in Acre (Brazil), two forms of Community Managed PAs, are effective in conserving carbon stocks and avoiding carbon emissions. Moreover, these Community Managed PAs were more effective than Other Lands (i.e., unprotected) and Sustainable Use PAs (i.e., IUCN V-VI or equivalent), and at least as effective as Strict PAs (i.e., IUCN I-IV or equivalent). Our findings illustrate that estimating temporal and spatial effects are key to distinguish local and jurisdiction-wide land-use dynamics among land tenures. We also make further progress towards confirming that decentralized governance may help PAs reach ecological and social targets. That is particularly relevant in the context of REDD+ as we show that when social organizations of forest communities build support relations with government institutions and international organizations, they may improve forest governance and contribute to climate change mitigation.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

All authors contributed to the conception and design of the study. CA, WW, and SG participated in data curation. CA performed the statistical analyses and wrote the sections of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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Data Availability Statement

The datasets generated for this study can be found in the Open Science Framework-OSF [https://osf.io/ejavd/].

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Linking statement 2

The previous findings exhibited that the domestic forests of Indigenous Peoples (Chapter 1) and Local Communities (Chapter 2) have a limited and stable impact on carbon stocks after accounting for the influence of market access and agriculture suitability through matching analysis and geographic discontinuity designs. These spatial-temporal carbon stocks dynamics suggest that Indigenous Peoples' and Local Communities' land use is mainly concentrated on land boundaries while conserving a core forest area. To further understand the dynamics of land use and potential forest stability, Chapter 3 analyzes the spatial-temporal patterns of deforestation and disturbances followed by recovery in Indigenous Lands (i.e., Indigenous Territories and their overlaps with Protected Areas) from Panama. These spatial-temporal dynamics of land use are linked to instrumental (e.g., food production) and relational (e.g., culture) values regarding nature to reveal the circumstances where forest stability could emerge.

Chapter 3. Diverse values regarding nature are related to stable forests: The case of Indigenous Lands in Panama

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Abstract

Land use decisions emerge from stakeholders' worldviews and values regarding nature. Governments and private actors have traditionally displayed a unidimensional worldview that favors specific values over others (e.g., food production and biodiversity), whereas Indigenous Peoples display a pluralistic valuation of nature that does not privilege values but aims to integrate them. Some studies have attempted to establish the relation between Indigenous land use and forest cover and, thus, the capacity of these landscapes to provide multiple values. However, most of these studies have focused on linear models of deforestation predictors. Less attention has been paid to non-linear interactions that may quantify where deforestation and other disturbances are concentrated or dispersed. Nor do they analyze the values involved in Indigenous land use that may explain these spatial-temporal patterns. To address these gaps, we analyzed deforestation and disturbance spatial-temporal patterns in Indigenous Territories and Other unprotected Lands in Panama between 2001 and 2020, using a continuous change detection algorithm and generalized additive models. Based on this analysis, we performed participatory mapping across three Indigenous Lands in eastern Panama to identify instrumental and relational values linked to land use. Our results show that disturbances followed by recovery have been the dominant cause of land-cover changes in Indigenous Lands, whereas deforestation is the prevalent change in Other unprotected Lands. Moreover, the area of stable forests until 2020 in Indigenous Lands was 2.3 times higher than in Other Lands. The non-linear models demonstrate that deforestation and disturbance in Indigenous Lands exhibit a low density, spatial concentration on forest edges, and temporal stability, explaining their relatively stable

forest cover for the past 20 years. 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 (sacred sites, cultural identity) are more dispersed in forests. Taken together, these results suggest that diverse values regarding nature, in this case, framed by Indigenous worldviews, can beget stability to forest cover, contributing to Indigenous People's quality of life, climate change mitigation, and biodiversity conservation.

Introduction

Land use decisions emerge from stakeholders' worldviews and values regarding nature (Ellis et al., 2019). For instance, Indigenous Peoples' worldviews integrate diverse values through land use practices that aim to positively contribute to nature and local livelihoods (Berkes et al., 2000). This pluralistic valuation does not privilege nature at the expense of food production and other livelihoods or vice versa but aims to integrate them (Villalba, 2013; Walsh, 2010). Instead, governments and private actors across the globe have usually promoted an economic worldview that privileges one value over others. This unidimensional valuation has resulted in land use policies such as titling deforested lands dedicated to food production (Angelsen, 2010), results-based payments for carbon sequestration (Sills et al., 2014), or establishing 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 (Ellis et al., 2019; Pascual et al., 2017). In neotropical forest lands, largely inhabited by Indigenous Peoples (Thiede & 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.

Different studies have analyzed the influence of Indigenous land use on tropical landscapes. Some have controlled the influence of socio-economic and environmental predictors to establish that Indigenous land use reduces deforestation and forests disturbances while conserving carbon stocks (Alejo et al., 2021; Baragwanath & Bayi, 2020; Blackman et al., 2017; Blackman & Veit, 2018; Bonilla-Mejía & Higuera-Mendieta, 2019; Nelson & Chomitz, 2011; Nolte et al., 2013; Sze et al., 2022). Other studies have attempted to establish if Indigenous land use results in stable forest cover and explore its potential predictors. Both expert (van Vliet et al., 2013) and household surveys (Gray et al., 2008) suggest that some Indigenous Lands display large agropastoral footprints and shortened fallows, questioning the capacity of Indigenous land use in maintaining stable forest covers. Recently, studies capturing land use over time and using household surveys (Gray & Bilsborrow, 2020), remote sensing (Kunz et al., 2022; Paneque-Gálvez et al., 2013; Puc-Alcocer et al., 2019), 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 thus, forest cover stability, depend on different socio-economic predictors such as the accessibility to markets (Coomes et al., 2022; Gray et al., 2008; Gray & Bilsborrow, 2020; van Vliet et al., 2013), and environmental predictors, including forest endowments and topography (Coomes et al., 2016; Sharma et al., 2016). Overall, these studies have focused on linear models that exhibit positive or negative interactions between a specific land use change (e.g., cultivated area) and some predictors. As yet, less attention has been paid to non-linear interactions that may quantify where both deforestation (forest to non-forest) and disturbance (temporal change in forest cover followed by regeneration) are concentrated and, thus, exhibit where forest cover remains stable.

The limited recognition of local worldviews and values has represented another gap in understanding Indigenous land use dynamics (Weiss et al., 2013). This limitation may explain the shift in research and policy discussion from the Ecosystem Services (ES) framework to the Nature Contributions to People (NCP) framework. The former reflects an economic worldview focusing on services to satisfy human ends or instrumental values, and the latter aims to recognize other worldviews (Díaz et al., 2018). For that reason, the NCP framework integrates relational values (i.e., values deriving from human-nature relationships) and intrinsic values (i.e., inherent values on nature) regarding nature (Hill et al., 2021).

Recent studies reflect this integrated approach and have examined the spatial patterns of instrumental and relational values regarding nature through participatory mapping. For instance, García-Nieto et al. (2019) mapped instrumental values, including food production and water supply, along with relational values associated with landmarks and leisure activities in rural communities in Spain. Ramirez-Gomez et al. (2016) delineated areas with instrumental and relational values for Indigenous communities in Guyana, revealing hotspots and overlaps among these values. Further, some studies have analyzed the spatial patterns of values according to environmental predictors. Alessa et al. (2008) mapped instrumental and relational values in Alaska to find that peoples' values related to the landscape may 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. Whereas these participatory studies reveal some spatial patterns of instrumental and relational values regarding nature, little is known about the relation of these values with land use change. Quantifying the spatial patterns of instrumental and relational values involved in Indigenous land use may reveal circumstances involved in forest cover stability or instability.

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). Here, we argue that Indigenous land use results from the spatial interplay of diverse instrumental and relational values on nature. Specifically, our study has two aims: (1) we use remote sensing between 2001 and 2020 at the national scale to compare the influence of environmental and socio-economic predictors on deforestation and forest disturbances in Indigenous Lands and Other Lands (i.e., public and private lands lacking a protected status); 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 socio-economic predictors on instrumental and relational values associated with land use. We show that the distinction between deforestation (forest to non-forest) and forest disturbances (temporal change in forest cover followed by regeneration) reveals land use patterns that hinder or facilitate forest cover stability. The participatory mapping in Indigenous Lands provides a novel approach to understanding which instrumental and relational values motivate land use change and forest cover stability.

Methods

Study Area

Our study national scale analysis was undertaken in Panama, a country that in 2000 maintained 76% of its land cover as primary forest and 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 examined the temporal and spatial patterns of deforestation and disturbance in lands held by Indigenous Peoples (Indigenous Lands) and public/private lands lacking protected status (Other Lands) (Figure 1A). Indigenous Lands, the focus of our study, are home to eight Indigenous groups (Velásquez Runk, 2012) and represent a mosaic of land tenure regimes. “Comarcas” have the status of a Province (i.e., State or Department), while other Indigenous Lands are usually defined as “Tierras Colectivas” (i.e., collective lands). Among “Tierras Colectivas,” some groups have obtained legal land titles, and others remain as claimed. Regardless of their legal status, Indigenous Lands often overlap with Protected Areas and currently cover ~ 41% of Panama’s area (Vergara-Asenjo & Potvin, 2014).

In addition to the national scale analysis, we explored at the local scale how instrumental and relational values regarding forests relate to the spatial patterns of deforestation and disturbance. To this end, we zoomed in on three Emberá Peoples' Indigenous Lands that exhibit different land use histories and levels of market access (Figure 1B and M1C). Piriatí and Ipetí are both located in the Bayano watershed, along the Pan-American Highway, and ~100 km from Panama City (Panama Province). These two Indigenous Lands were settled after the relocation of inhabitants living along the Bayano River during the 1970s due to hydroelectric dam construction and related flooding, and they were granted collective titles between 2014 and 2015 (Sharma et al., 2016). Shifting cultivation 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 province of Darién, 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 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 shifting cultivation, hunting, fishing, and the extraction of timber and non-timber forest products.

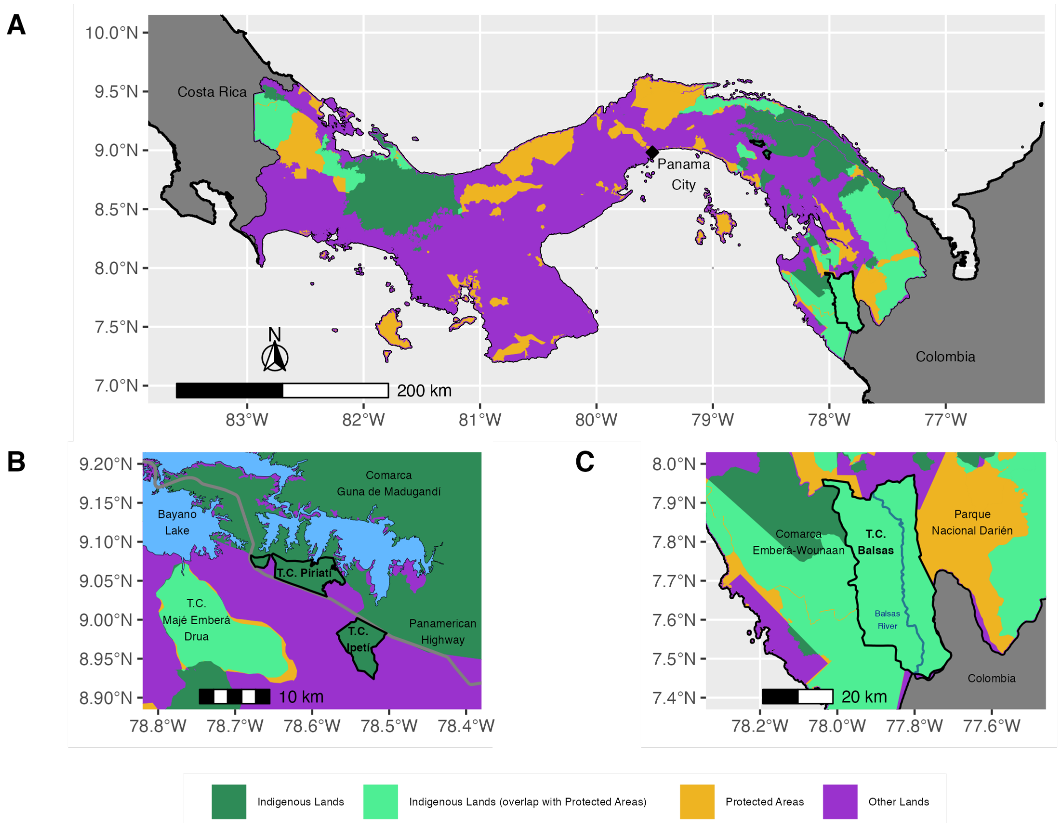

Figure 1. Study Area and the distribution of Indigenous Lands, Other Lands, and Protected Areas (excluded from the study). A. National scale of the study: Panama's Indigenous Lands and Other Lands. B. Local scale of the study: Indigenous Lands ("Tierras Colectivas") of Piriatí and Ipetí (Bayano watershed, Province of Pánama). C. Local scale of the study: Indigenous Land ("Tierras Colectivas") of Balsas (Balsas watershed, Province of Darién).

Geospatial data and processing

Our national and local scale datasets comprised geospatial information on deforestation, disturbance, land tenure, environmental and socio-economic predictors, district, and municipality (Table 1, Figure 2). Deforestation and disturbance were estimated using CODED (Continuous Degradation Detection, Version 1) (Bullock, Woodcock, Souza, et al., 2020). This Google Earth Engine (GEE) algorithm relies on Landsat imagery to calculate the "Normalized Degradation Fraction Index" (NDFI) on pixels' time series (Bullock, Nolte, et al., 2020). 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, Woodcock, & Olofsson, 2020; Reygadas et al., 2021). These steps result in a land-cover map classifying deforestation, disturbance, non-forest (i.e., areas that did not correspond to forest cover in 2000), and stable forest (i.e., undetected deforestation or disturbance). CODED also provides the date of deforestation and disturbance events. We used Hansen et al. (2013) data to create a forest mask in 2000 to delineate the detection of deforestation and disturbance in the period 2001-2020, 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 periods, each of five years (i.e., 2001-2005, 2006-2010, 2011-2015, and 2016-2020).

Based on CODED's land cover map from the period 2001-2020, we performed an accuracy assessment and area estimation of deforestation, disturbance, stable forest, and 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 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 Labs PBC, 2021), allowed us to determine if an observation actually corresponded to the land-cover category detected by CODED. We used the plugin AcATAMA in QGIS for these records (Llano, 2022). Instead of pixel counting, the resulting error matrix and a stratified estimator were used to calculate the confidence intervals for the land cover area categories (Arévalo et al., 2020; Olofsson et al., 2014). The accuracy assessment (Supplementary Material 1) and area estimation were followed by calculating the density of deforested and disturbed pixels per squared kilometer. A deforested or disturbed pixel is referred to as a "plot". Instead of estimating the area, we use plots/km2 to have a density measure comparable to the value points obtained through participatory mapping (see below). Deforestation and disturbance densities were outcome variables at the national and local scales.

Land tenure was a factor in the national scale analysis. The choice of this factor resulted from discussions about the study design among some co-authors (M.O. and C.A.) and Indigenous Leaders from Piriatí, Ipetí, and Balsas Indigenous Lands. M.O. and Indigenous leaders underscored the relevance to illustrate the contrasts of land use patterns between Indigenous Lands and Other Lands. Thereby, land tenure was defined from data curated by the Neotropical Ecology Laboratory (McGill University, Smithsonian Tropical Research Institute - STRI) 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” (titled or claimed), here defined as Indigenous Lands. The portions of Protected Areas that are not currently claimed as Indigenous Lands were excluded from the study. Other private and public areas without the status of Indigenous Land or Protected Area were defined as Other Lands.

We included multiple environmental and socio-economic predictors of deforestation and disturbance. Slope (Jarvis et al., 2008; Reuter et al., 2007), 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) and adopting the same methods to estimate river distance. The forest edge is a point of reference to determine the depth of deforestation and disturbance within forested areas or patches.

Population density (WorldPop & CIESIN - Columbia University, 2020) and road distance (CIESIN - Columbia University & ITOS - University of Georgia, 2013) were used as socio-economic predictors. To account for the influence of other local socio-economic conditions, we identified districts and municipalities (“Corregimientos”, smallest political division unit) in Indigenous Lands and Private Lands from the Global Administrative Areas database - GADM (2022). As explained below, the district and municipality were not predictors but random effects. 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 (1km X 1km cells). Except for the distance to rivers and forest edge, the geoprocessing of tenure, environmental and socio-economic predictors, and administrative subdivisions were performed with the R packages sf (Pebesma, Bivand, et al., 2021) and stars (Pebesma, Summer, et al., 2021).

Participatory mapping

To carry out our study at the local scale, we obtained an ethical certificate for research involving human participants from McGill University Research Ethics Board (File Number: 21-03-023). Additionally, the approval of the study was granted by community-level meetings with Caciques and Nokos (i.e., Indigenous leaders) in Piriatí, Ipetí, and Balsas. At this local scale, we performed participatory mapping to identify instrumental and relational values regarding forests. Our study conceived these values as principles and preferences, given a cultural context, that acknowledge humans' interdependence with nature and its contributions to a good quality of life (see Pascual et al., 2017). Following the nature's contribution to people framework (Díaz et al., 2018; Hill et al., 2021; Pascual et al., 2017), 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., culture). 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.

Variable category	Spatial variables	Time period	Original resolution	Source
Factors and random effects	Land tenure: Indigenous Lands and Other Lands	2000-2020	NA	Neotropical Ecology Lab. (STRI, McGill University) and UNEP-WCMC & IUCN (2021)
	Districts and municipalities	2022	NA	Global ADMinistrative Areas (GADM) (2022)
Environmental Predictors	Slope (deg.)	NA	90 m.	CGIAR-SRTM V4 (Jarvis et al., 2008; Reuter et al., 2007)
	Travel time to the nearest city of 50,000 or more people (min.)	2000	920 m.	(Nelson, 2008)
	Distance to rivers (km)	2022	250 m.	STRI (2022) and own calculations
	Forest cover	2000	30 m.	Hansen et al. (2013)
	Distance to forest edge	2000	250 m.	Hansen et al. (2013) and own calculations
Socio-Economic Predictors	Population density - UN adjusted (people/km2)	2000, 2005, 2010, 2015	1 km.	Worldpop and CIESIN – Columbia University (2020)
	Road distance (km)	2010	250 m.	CIESIN - Columbia University and ITOS - University of Georgia (2013) and own calculations.
Outcome variables	Deforestation and disturbance	2001-2020	30 m.	Landsat, CODED algorithm in Google Earth Engine (Bullock, Woodcock, Souza, et al., 2020)
	Instrumental and relational values in Indigenous Lands	2021	NA	Participatory mapping

Table 1. Geospatial variables included in the study.

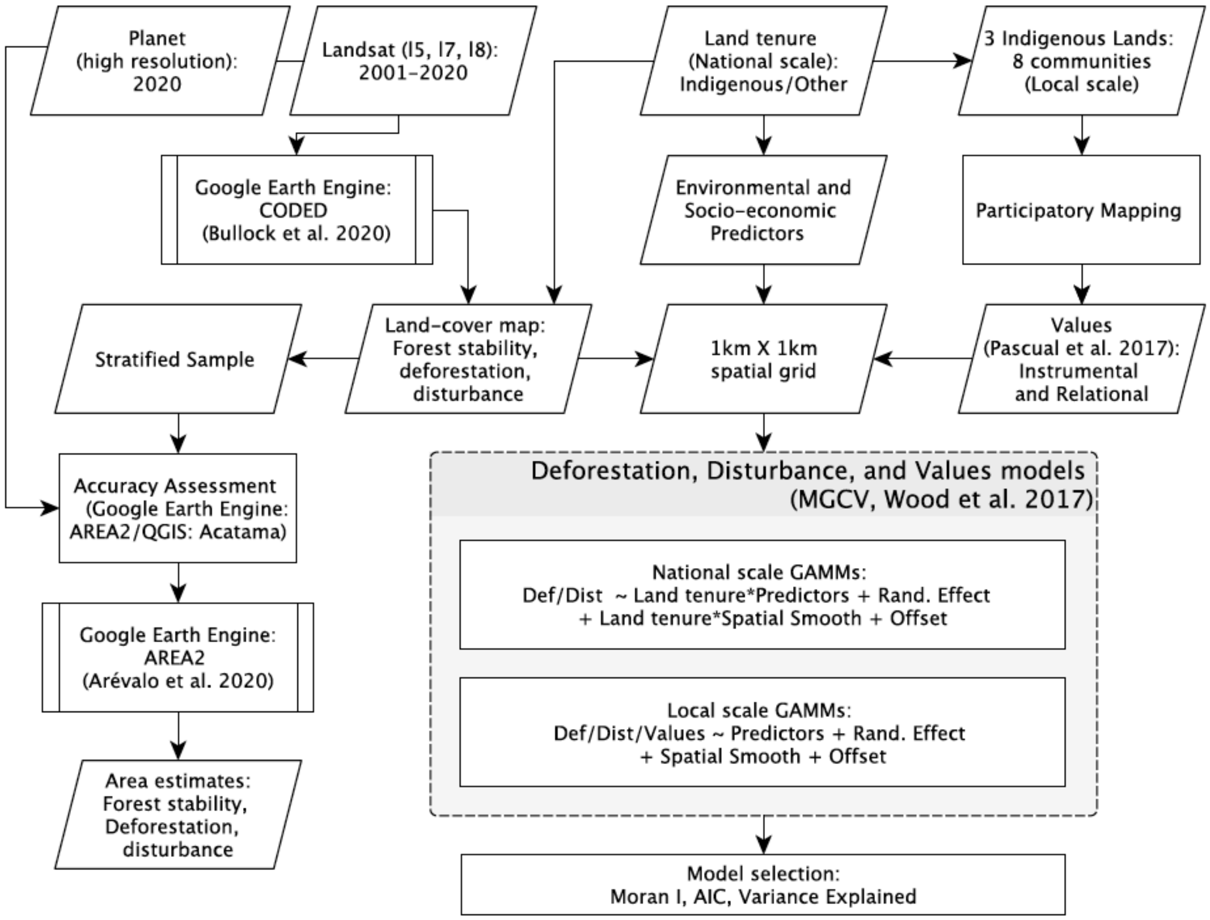

Figure 2. A flowchart representing the methodology of our study. The study's national scale Generalized Additive Mixed Models (GAMMs) include Land tenure as a factor (Other Lands/Indigenous Lands) for all predictors. The local scale focuses on Indigenous Lands and includes GAMMs on values regarding nature. The Random Effects were Municipality and Indigenous Land at the national and local scale, respectively. 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 locations valued by the Emberá's culture; that is, relational 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) Culture. We presume that the first category is related to deforestation and disturbance, whereas the second may only correspond to disturbance. Considering that we focus 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 cultural values in these three Indigenous Lands. The density of instrumental and cultural values were outcome variables on the local scale.

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 (Supplementary Material 2). At the national scale, the models' outcome variables were deforestation and disturbance density (plots/km2) in the period 2001-2020 and five-years 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 2001-2020 (plots/km2) along with forest values densities (points/km2). The models included non-linear interactions between the outcome variables and the environmental and socio-economic 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), and land tenure (Other Lands/Indigenous Lands) was a factor for all predictors at the national scale. The models also included random effects: district and municipality at the national scale, and Indigenous Land 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 & 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 5 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 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 culture) 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 (Supplementary Material 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 third criteria. 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). Spatial autocorrelation was assessed with the package spdep (Bivand, 2022) using the functions nb2listw (creates a weighted list of neighbors) and moran.test. These resulted in two final models at the national scale and five final models at the national scale. To compare the deforestation and disturbance models at the national and local scales, we then estimated the relative importance of each explanatory variable (i.e., environmental and socio-economic 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 Indigenous Lands. Specifically, we determined how the outcome variables (i.e., deforestation, disturbance, food from agriculture, food gathering and household materials, and culture), and socio-economic and environmental predictors explained differences between Piriatí, Ipetí, and Balsas. After the LDA, we performed Vegan Canonical Correspondence Analyses (CCA) to examine the relationships between the outcome variables and socio-economic and environmental predictors. The CCA is a weighted Redundancy Analysis (RDA), which consists of a multivariate multiple linear regression followed by a 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

To analyze the spatial patterns of deforestation and forest disturbance in Indigenous Lands and Other Lands lacking a protected status in Panama, we estimated land-cover changes between 2001 and 2020. The land-cover change detection algorithm, CODED, had an overall accuracy of ~ 91% (Supplementary Material 1) and allowed us to estimate the land area that was deforested (i.e., forest to non-forest), disturbed (temporal change in forest cover followed by regeneration), or remained as either stable forest (i.e., undetected deforestation or disturbance) or non-forest (Figure 3, Supplementary Material 3). Between 2001 and 2020, the area deforested was almost five times higher in Other Lands than in Indigenous Lands., i.e., 3482.77 km2 ($\pm$ 113.92 km2 95% CI) in the former and 711.58 km2 ($\pm$ 62.56 km2) in the latter. Forest disturbances occurred in 1238.36 km2 ($\pm$ 269.26 km2) and 1444.34 km2 ($\pm$ 180.83 km2) in Other Lands and Indigenous Lands, respectively. Moreover, the area of stable forests until 2020 in Indigenous Lands (18537.74 $\pm$ 1052.32 km2) was 2.3 times higher than in Other Lands (7973.77 $\pm$ 1398.68 km2). Thus, relative to forests before 2000, 27.43% were deforested, and 9.75% were disturbed in Other Lands. The same comparison in Indigenous Lands implies that 3.33% of forests were deforested, while 6.98% were disturbed. These results suggest that between 2001 and 2020, deforestation was the dominant cause of land-cover change in Other Lands. Instead, forest disturbance was the leading cause in Indigenous Lands, where most of the forest cover remained stable.

After estimating the area of land-cover change and stability at the national scale, we inferred the spatial patterns of deforestation and disturbance densities in Indigenous Lands and Other Lands. The models included non-linear interactions with environmental and socio-economic predictors, a spatial smooth function to control for spatial autocorrelation, land tenure as a factor for these variables, and district and municipality as random effects. The best model for both outcome variables contained a spatial smooth function with a Gaussian process and exponential correlation structure (Supplementary Material 4). The models had an explained deviance of 75.39% in deforestation density (AIC = 448268.13, Moran's I = 0.0198 $p < 0.0001$) and 65.17% in disturbance density (AIC = 270685.59, Moran's I = 0.0063 $p < 0.0001$). All variables included in the deforestation and disturbance models were significant ($p < 0.0001$) (Figure 4). District and municipality explained most of the model deviance of deforestation and disturbance (61% and 90%, respectively). The distance to forest edge (9-2%), spatial smooth (8-1%), travel time to city (10-3%), and road distance (7-3%) followed in explained deviance. Slope and distance to rivers explained 3% or less of the deforestation and disturbance deviance at the national scale (Supplementary Material 5). The importance of the district, municipality, and the spatial smooth function 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 socio-economic predictors do explain the spatial patterns of deforestation and disturbance on the national scale.

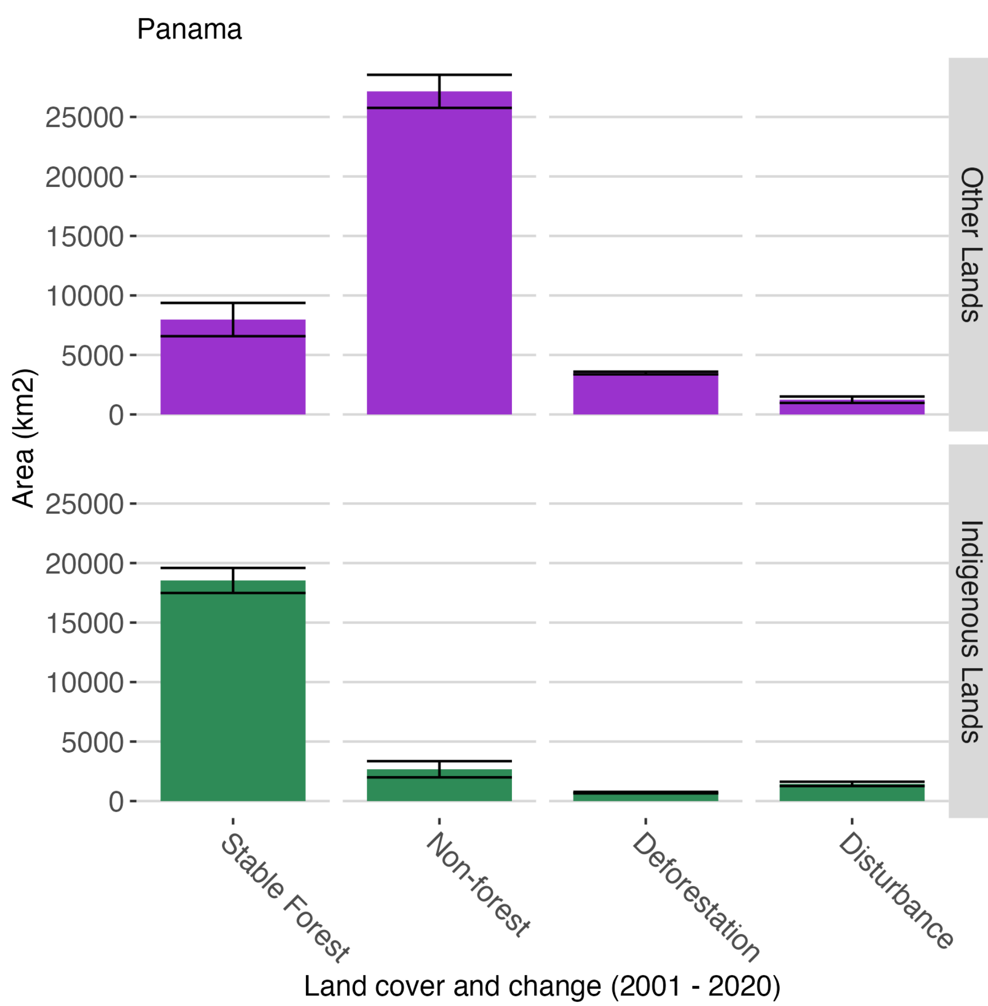

Figure 3. Land cover and change in Indigenous Lands and Other Lands for Panama in the period 2001-2020. Deforestation refers to the conversion of forest to non-forest land cover. Disturbance is a process that does not lead to a permanent change in forest cover and is followed by regeneration. Non-forest corresponds to areas that did not correspond to forest cover in 2000.

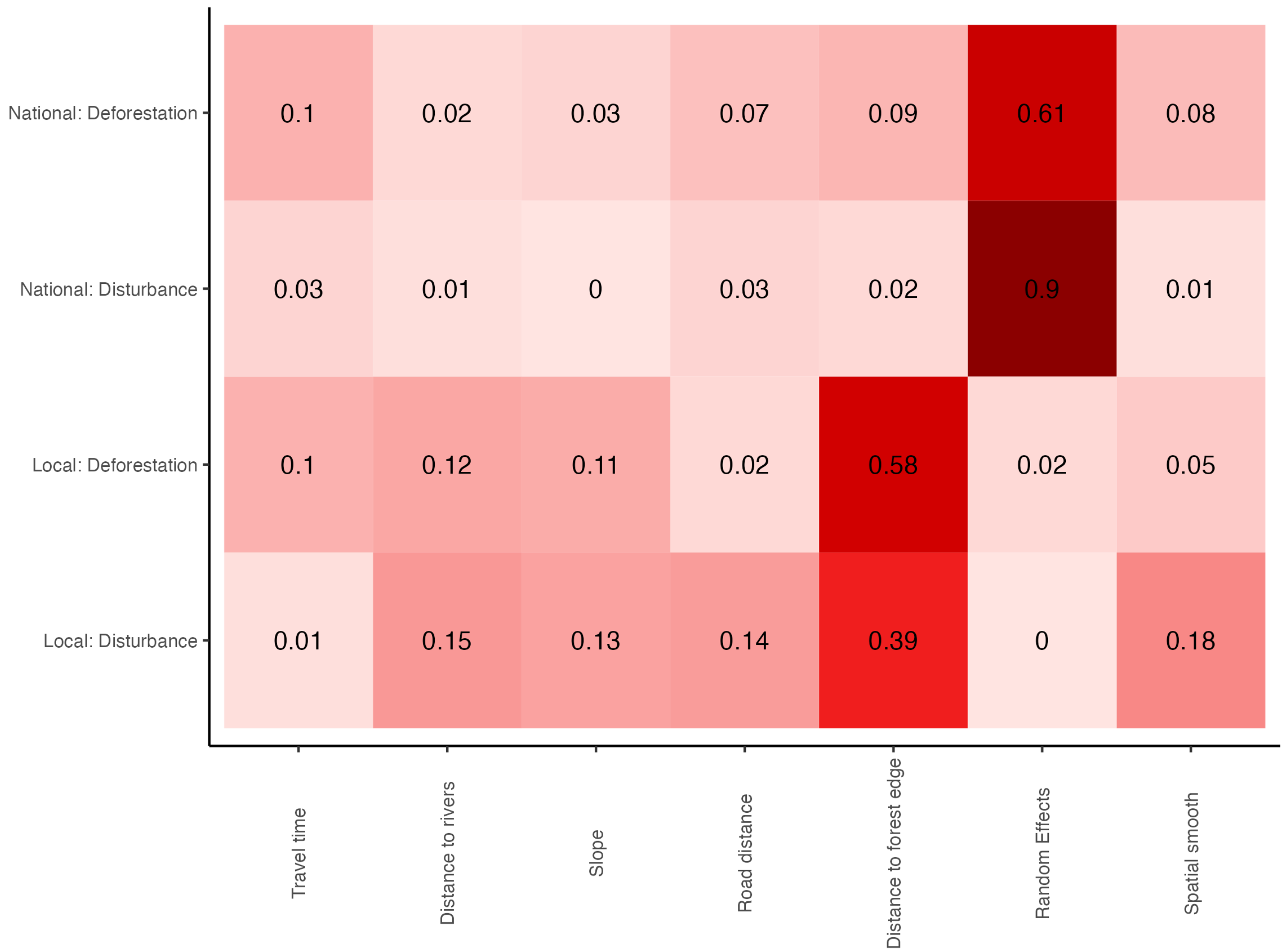

Figure 4. Variable importance for Generalized Additive Mixed Models (GAMMs) predicting the spatial patterns of deforestation, disturbance, and values on forests at the national (i.e., Panama) and local scale (i.e., Indigenous Lands of Piriatí, Ipetí, and Balsas in eastern Panama).

Despite the limited influence of roads and travel time to cities on deforestation and disturbance, these predictors reveal patterns at the national scale (Figure 5). Deforestation and disturbance concentrations were moderately high in Panama's most accessible areas to cities. Both deforestation and disturbance in Other Lands were particularly dense between 0 and 500 min. (~8 hours) of traveling to cities (up to 2 plots/km2). Additionally, deforestation in Other Lands displayed an increase in the least accessible areas (>1250 min. of traveling). In Indigenous Lands, both deforestation and disturbance also showed their highest densities close to cities (~ 2.5 plots/km2) and constantly decreased to the least accessible areas. Across Indigenous Lands, deforestation and disturbance were around 2.5 plots/km2 or below at multiple distances from roads and had an overall trend to decrease. The density of these land use changes was lower in Other Lands (< 2 plots/km2), especially next to roads (< 1.2 plots/km2), and as travel time, deforestation tended to increase in the least road accessible areas. These results exhibit that travel time to cities, and road effects vary between Indigenous Lands and Other Lands, but within the same land tenure, there is less variation between deforestation and disturbance.

As other predictors, the distance to forest edge effect on land-cover changes was strongly influenced by land tenure. Overall, deforestation and disturbance densities decreased inside forest patches, and their magnitudes considerably differed between Other Lands and Indigenous Lands. At forest edges in Other Lands, deforestation and disturbance densities were approximately 25 and 7 plots/km2, respectively, and dropped to zero at approximately 4 km inside forest patches. Conversely, deforestation and disturbance were between 6-3 times less dense at forest edges in Indigenous Lands (4.5, 2 plots/km2, respectively). Nevertheless, low deforestation and disturbance events (~ 1 plot/km2) seem to occur more than 4 km inside these forest patches. These contrasting patterns between land tenure regimes indicate that Indigenous land use exhibit a low density, spatial concentration on forest edges, and temporal stability (Supplementary Material 6), explaining their relatively stable forest cover for the past 20 years.

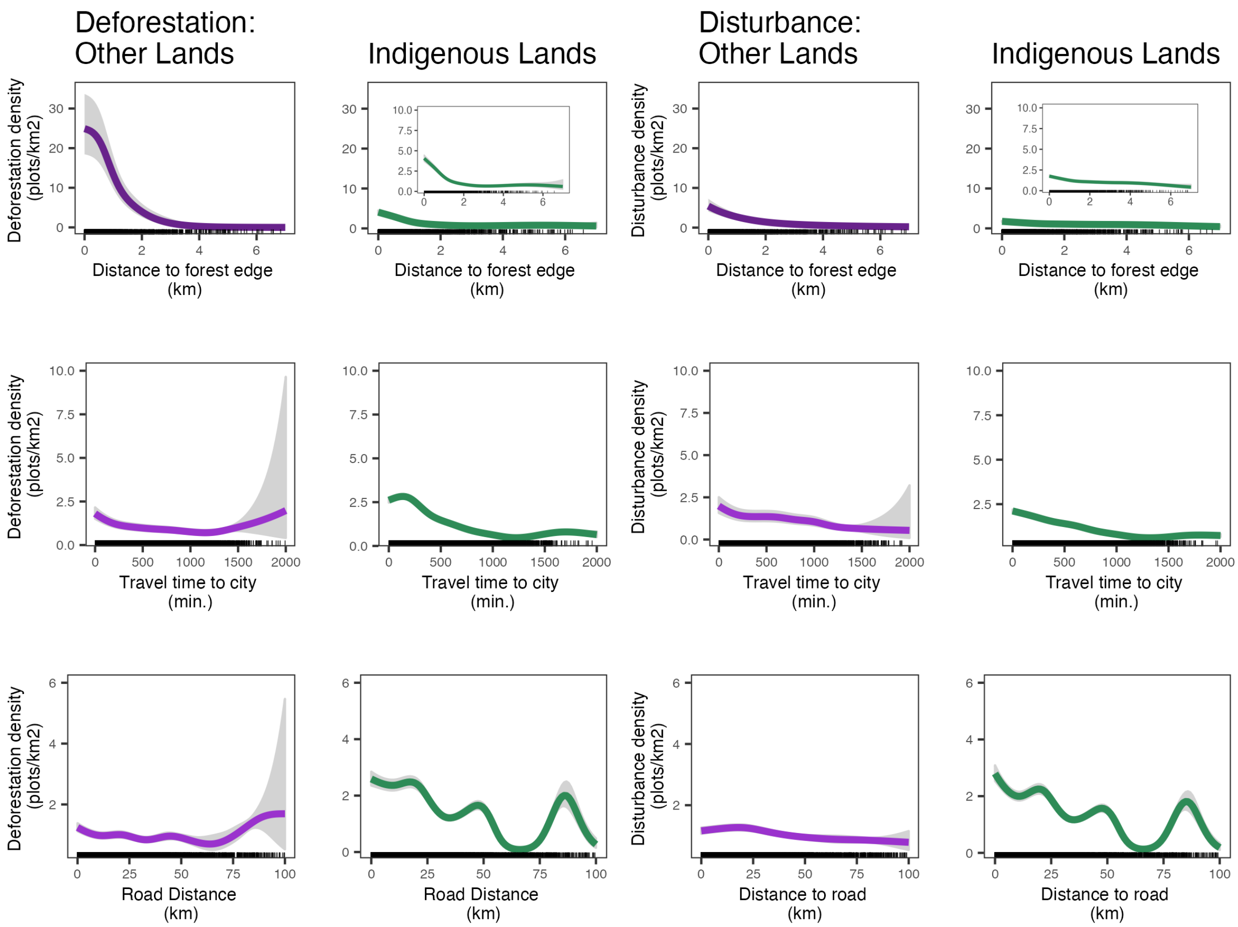

Figure 5. The effects of environmental and socio-economic predictors on deforestation and disturbance density at the national scale during 2001-2020. The national scale compares Indigenous Lands and Other Lands in Panama. A plot represents a ~30 m resolution pixel.

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 88.68% in deforestation density (AIC = 2083.82, Moran's I = -0.0024) and 73.42% 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, in this case, Indigenous Land, which accounted for the variation among Piriatí, Ipetí, and Balsas. The random effects ($p > 0.1$) for both models and the spatial smooth in the deforestation model ($p < 0.001$) had lower importance (< 5%) than in the national scale models, which is expected given the reduced geographic area (Supplementary Material 2, Figure 4). Relative to the national scale models, the distance to rivers and slope had greater importance (11-15%, $p < 0.001$) (Supplementary Material 7). Similarly, the distance to forest edge was significant ($p < 0.0001$) and explained most of the deviance in the deforestation and disturbance models (58-39%)(Figure 4), and therefore is the focus of the local scale analysis (Figure 6). Deforestation density on average was approximately 12 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 ~ 6 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 us to identify the spatial patterns of three categories of values: food from agriculture; food gathering and household materials; and culture. 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 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 (~20 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 (~12 and 6 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 (Figure 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 (Figure 6). According to participatory mapping groups, there are occasional extractions of household materials throughout tributaries, explaining 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.

Cultural forest values were related to 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 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 cultural values reached their maximum density next to rivers (3.8 points/km2) and at 40 degrees of slope (3 points/km2) (Supplementary Material 8). As in the case of food from gathering and household materials, the cultural values were widely dispersed across forest patches (Figure 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 between them. The LDA classified Indigenous Lands based on outcome variables (i.e., deforestation, disturbance, and values) and predictors (i.e., environmental and socio-economic) (Supplementary Material 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 53.8 % and 79.5 %, respectively, and suggest 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.

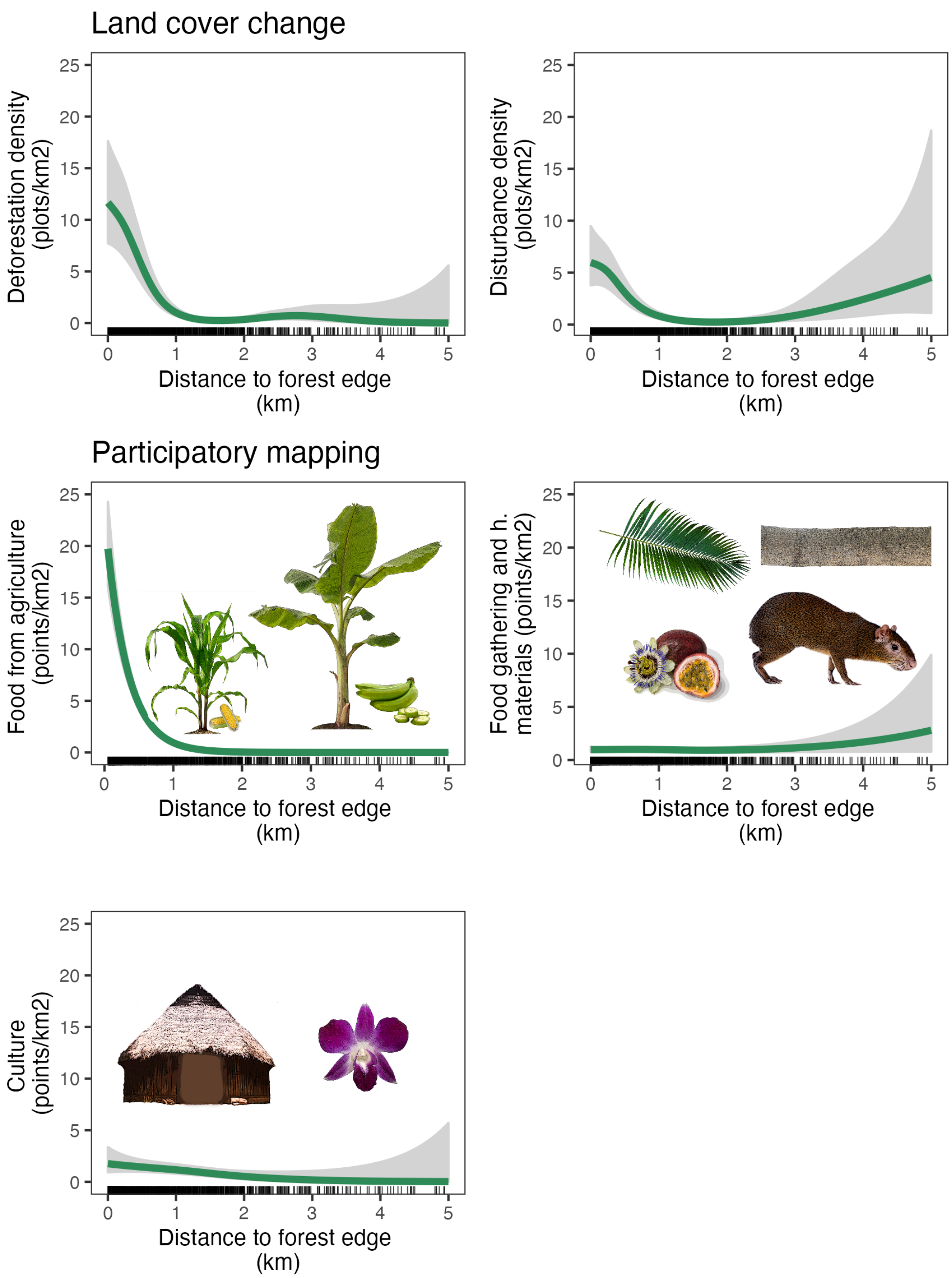

Figure 6. The spatial patterns of deforestation, disturbance, and forest values across forest patches at the local scale (Emberá Indigenous Lands of Piriatí, Ipetí, and Balsas from eastern Panama). A plot represents a ~30 m resolution pixel derived from remote sensing. A point represents a location obtained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

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 (Supplementary Material 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 99.22%, and 96.33% corresponded to the first axis. Likewise, the variances explained for the Balsas watershed were 94.81% and 83.88%, 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, road distance and travel time to cities had a higher loading in Bayano (0.67, - 0.26) than in Balsas (-0.54, - 0.06). Conversely, the distance to rivers had a higher loading in Balsas (-0.49) than in Bayano (0.01). The distance to forest edge had the highest loading in both Balsas (-0.92) and Bayano (0.73). Based on these results, we interpret that land use changes and values were primarily influenced by the socio-economic 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 and Other Lands lacking protection from Panama. Unlike previous studies focusing on deforestation, we integrate forest disturbances and Indigenous values regarding forests into our analysis. At the national scale, we find that the dominant cause of land-cover change is deforestation in Other Lands and disturbance in Indigenous Lands. According to different environmental and socio-economic predictors, deforestation and disturbance are spatially limited in Indigenous Lands, explaining the stability of forest cover. At the local scale, 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 occurs where deforestation and disturbance are more concentrated. In contrast, other instrumental and relational values are more dispersed in forests.

Contrasts between land use on Indigenous and Other Lands

The national scale results highlight two critical differences between Indigenous Lands and Other Lands. First, land cover change and stability display opposite trends. 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). 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.

The second difference emerges from the influence of predictors for land-cover change. Deforestation and disturbance in Other Lands and Indigenous Lands show high densities in the most accessible areas to cities. These patterns are partially explained by Panama's land use history, where most agricultural development has concentrated around urban centers in the driest and more suitable lands for cattle and agriculture (Wright & Samaniego, 2008). Additionally, there was an increase in deforestation in Other Lands' least accessible lands, which seem to correspond to the most remote locations of 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 (Darién, 2021). Moreover, our results show that roads had a larger and more variable effect on deforestation and disturbance in Indigenous Lands than in Other Lands. We suspect that land invasions in Indigenous Lands over the past two decades partially explain this pattern (Vergara-Asenjo et al., 2017). These results highlight that deforestation and disturbance may display heterogeneous distributions that linear models might not detect, revealing distinctive land use legacies and pressures in Indigenous Lands and Other Lands. Furthermore, we control for spatial autocorrelation, reducing biases when modeling deforestation and disturbance predictors (Mets et al., 2017).

Our results also show that deforestation and disturbance in Indigenous Lands had a more limited effect on forest patches than in Other Lands. Specifically, we demonstrate that Indigenous lands use exhibits a low density, spatial concentration on forest edges, and temporal stability, explaining their relatively stable forest covers for the past 20 years. These spatial patterns are similar to those found by Coomes et al. (2022) in the Peruvian Amazon, where fallows (i.e., disturbances) around Indigenous communities are more dispersed than in folk communities. Furthermore, our combined national and local scale results are consistent with studies showing that Indigenous land use is relatively stable (Coomes et al., 2022; Gray & Bilsborrow, 2020; Paneque-gálvez et al., 2013; Puc-Alcocer et al., 2019; Toledo et al., 2003), reduces forest fragmentation (Cabral et al., 2018), and maintains biodiversity (Leung et al., 2019).

Indigenous land use and 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 centers are typically dedicated to shifting agriculture, given the difficulties and costs of transporting agricultural produce (Coomes et al., 2022; Jakovac et al., 2017). 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, the fact that forests in Other Lands have experienced contrasting patterns of deforestation and disturbance indicates that other values in Indigenous Lands might influence forest cover stability.

Compared to food from agriculture, our results show 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 (Coomes, 2004; Dalle et al., 2002; Velásquez Runk, 2001). Moreover, it's been found that > 20% of hunting events are opportunistic and related to agriculture and fishing (Read et al., 2010; Smith, 2008). Our results do 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 & Coomes, 2022). Dalle et al. (2002) found that among the neighboring Kuna people in eastern Panama, particular 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 cultural 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 cultural values imply a lack of preference for unique species or habitats. Indeed, similar to the Anishnabee in the boreal forests of Canada (Berkes & Davidson-Hunt, 2006), all elements from the Embera's land have some value and should be maintained for future generations. The association of higher cultural value with landmarks such as rivers, mountains, rocks, or particular forest areas that, 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. "Topograms" in our study seem to articulate well with the cultural identity of the Emberá and the traditional institutions that limit land use. Our results illustrate that it is not the exclusive influence of environmental and socio-economic conditions that limit the expansion of deforestation and disturbance but rather the interplay of these conditions with diverse instrumental and cultural values that bring stability to forest cover.

This type of landscape with limited spatial extents and land use densities that provide diverse values has been suggested in different contexts and scales. 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 and actors (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 from relational values.

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 (Darién, 2021; Herlihy, 2003). In fact, the Emberá of Balsas have been seeking title to their lands 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 cultural values linked to the future, such as reforestation projects (Shinbrot et al., 2022; Sloan, 2016), as a way to restore their landscape and revitalize the Emberá ways of life. Participants in Balsas mapping mentioned more often cultural 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.

Caveats

We identify 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 & Chazdon, 2017). Considering that the detection of forest disturbances in our study involves the loss and recovery of some spectral attributes, we cannot establish that those changes necessarily imply forest degradation from an ecological perspective.

Moreover, the producer's accuracy for disturbances was ~60%, implying that ~40% of these land cover changes were not detected by the algorithm CODED, and may question our interpretations concerning forest cover stability and values regarding nature. According to Reygadas (2021), CODED is conservative in detecting riverine disturbances but sensitive enough to detect shifting cultivation practices. If some disturbance events were undetected in these landscape segments, our interpretations remain unchanged: disturbance and deforestation events tend to be concentrated next to rivers. The detection of disturbances on forest edges represents another potential source of error. However, CODED is particularly sensitive in detecting land cover changes on forest edges and classifying them as disturbances in forest-dominated areas (Bullock et al., 2020; Reygadas et al., 2021). We also rule out the lack of detection of considerable changes inside forest patches as CODED excels similar algorithms in detecting informal logging roads (Reygadas et al., 2021). These trade-offs suggest that undetected disturbances, and possibly deforestation, seem to correspond to subtle events dispersed on the landscape that can’t be detected from Landsat’s spatial and temporal resolution and do not alter the general interpretations of our study.

Second, our national and local models better explained deforestation than forest disturbance. The most contrasting models were found between Indigenous Lands and Other Lands, whereas deforestation and disturbance in the same land tenure regime displayed similar patterns but different magnitudes. Including additional predictors may shed further light on the differences between land cover changes.

Finally, our study provides a spatial understanding of select categories of instrumental and relational values regarding forests that we found are related to land use dynamics. Future studies could explore the potential fluidity and overlaps among instrumental, relational, and intrinsic values (Pascual et al., 2017); and the differences in values perceptions concerning gender (Sharma et al., 2015), age (Vélez & López, 2013), seasonality, and occupation (Asatrizy-Kumua et al., 2020).

Conclusion

The state of tropical forests in Indigenous Lands exemplifies complex social-ecological systems where 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 socio-economic and environmental conditions so as to gauge the "net effect" of Indigenous Lands on forest conservation (Alejo et al., 2021; Blackman & Veit, 2018; Sze et al., 2022; Vergara-Asenjo & Potvin, 2014). Our study provides a complementary contribution by analyzing the influence of socio-economic 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 temporally stable. These patterns reflect instrumental and relational values: agriculture for food production is concentrated on forest edges, whereas gathering food and household materials, and cultural values are dispersed throughout forests. Taken together, these results suggest 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.

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General Discussion

This thesis was based on two premises: first, conserving and improving the management of existing neotropical forests is one of the most important land contributions to limiting global warming to 1.5°C. Second, conservation and forest management in the neotropics heavily rely on Indigenous Peoples and Local Communities (IPLC) that have been traditionally managing and domesticating these ecosystems for decades to millennia. Although considerable research has focused on the effect of IPLC lands and related policy interventions on deforestation, few studies have explored their influence on forest stability indicators and the relation of these indicators with inherent values regarding nature. Based on the two premises aforementioned and these gaps, this thesis aimed to answer the question: How do IPLC's land tenure, external policy incentives, and local values influence forest cover and carbon stocks stability in the neotropics? I focused on Indigenous Peoples that have traditionally inhabited neotropical forest lands and Local Communities that have created social organizations involved in forest management (i.e., forest community associations from Petén, Guatemala, and rubber tappers, from Acre, Brazil).

The first two chapters relied on matching analysis and geographic discontinuity designs to correct spatial location biases and estimate the effect of a land tenure regime relative to a control (i.e., quasi-experimental method). The first chapter estimated the temporal and spatial effects of three land tenure regimes on aboveground carbon stocks in Panama and four Amazon Basin countries. To further understand the diversity of governance systems in Protected Areas (PAs) and incentives to avoid land-use emissions, Chapter 2 aimed to assess the effectiveness of Community Managed PAs on forest carbon dynamics before and after the adoption of REDD+ programs. Chapter 3 delved into analyzing the spatial patterns of land use and values regarding nature in Indigenous Lands from Eastern Panama. Below, I discuss the main results and the implications in climate change mitigation, forest resilience and landscape management, and policy interventions.

Indigenous Peoples' and Local Communities' domestic forests stability

Previous studies demonstrate that inside IPLC lands, there is a net reduction in deforestation and disturbance that spans over a period of time (e.g. Blackman, 2015; Blackman et al., 2017; Nolte et al., 2013; Sze et al., 2022). Other studies attempt to identify the temporal variation in land use changes from one period of time to another (Pfaff et al., 2014). Exploring this temporal variation, my results suggest that IPLC lands in six countries result in limited changes in carbon stocks (Chapters 1 and 2), land use, and forest cover (Chapter 3) on an annual or periodical basis when compared to different land tenure regimes. Additionally, the quasi-experimental methods in the first two chapters served to demonstrate that Indigenous Lands and Community Managed PAs contribute to carbon stocks' stability due to an inherent influence, presumably because of local worldviews and management practices, and independently of reduced market access and agriculture suitability. The sensitivity analysis demonstrated that unmeasured covariates would require significant strength to explain away the inherent influence of Indigenous Lands and Community Managed PAs to maintain stable carbon stocks. The twenty years assessment in Panama (Chapter 3) exhibits that carbon stocks dynamics in Indigenous Lands may result from limited land use changes, mostly driven by disturbances followed by recovery and less driven by deforestation, while an extensive area of forest cover remains stable. As explained below, these spatial patterns are linked to local worldviews and values. Consequently, the most relevant and, perhaps, the most novel contribution of my thesis is related to the capacity of IPLC to bring stability to carbon stocks and forest cover in the neotropical domestic forests.

However, a temporal understanding of carbon stocks and forest cover does not reveal the spatial distribution of land use changes in IPLC domestic forests. Land use spatial patterns have different ecological and forest management implications compared to concentrated land uses. In contrast with concentrated land uses, homogenously dispersed land uses increase the number of forest fragments, reduce forest fragments' size, and end up exposing newer areas to land use change (Taubert et al., 2018). Other studies relying on a spatial analysis have shown that deforestation reduces inside the boundaries of Indigenous Lands (Baragwanath & Bayi, 2020), but not necessarily in PAs that allow sustainable use (Bonilla-Mejía & Higuera-Mendieta, 2019). My findings build upon these studies and suggest that inside the boundaries of Indigenous Lands (Chapter 1) and Community Managed PAs (Chapter 2) in neotropical countries, land use tends to gradually reduce towards the least accessible forests, limiting the impacts on carbon stocks, and potentially bringing stability to core forest areas. Moreover, I demonstrate that this spatial effect is stable over time. The robustness of these findings is supported by quasi-experimental methods that control for market access and agriculture suitability covariates, falsification tests on these covariates, and the control of geographic distance (i.e., two comparable observations might be at the same distance to a land tenure boundary but being far apart from each other). These methods have been suggested in the literature but are rarely applied together (Keele et al., 2015). Furthermore, the sensitivity analyses demonstrate that the influence of Indigenous Lands and Community Managed PA on carbon stocks stability is exceptionally robust in the least accessible core forest areas.

The spatial-temporal patterns of land use change in Indigenous Lands from Panama (Chapter 3) confirm those related to carbon stocks. After controlling for spatial autocorrelation and using non-linear modeling, I illustrate that both deforestation and disturbance are dense on the edge of forest patches. Both changes rapidly decrease in core areas, even though disturbance can still occur in low densities. Furthermore, the spatial patterns of deforestation and disturbance display minimum variation between time periods. On the one hand, my findings highlight the need for spatial-temporal methods to understand land use dynamics in forest lands. On the other hand, through two different approaches (i.e., quasi-experimental and non-linear modeling), they indicate that in the domestic forests, IPLC rely on a concentrated area for land use, usually accessible lands found close to legal or claimed boundaries, settlements, rivers, and forest edges, allowing for a forest core area to remain stable spatially and temporally (Figure 1). These spatial-temporal carbon stocks and forest cover patterns demonstrate that IPLC's forest management in the neotropical domestic forests could offer guidance to design sustainable land uses for climate change mitigation and forest conservation.

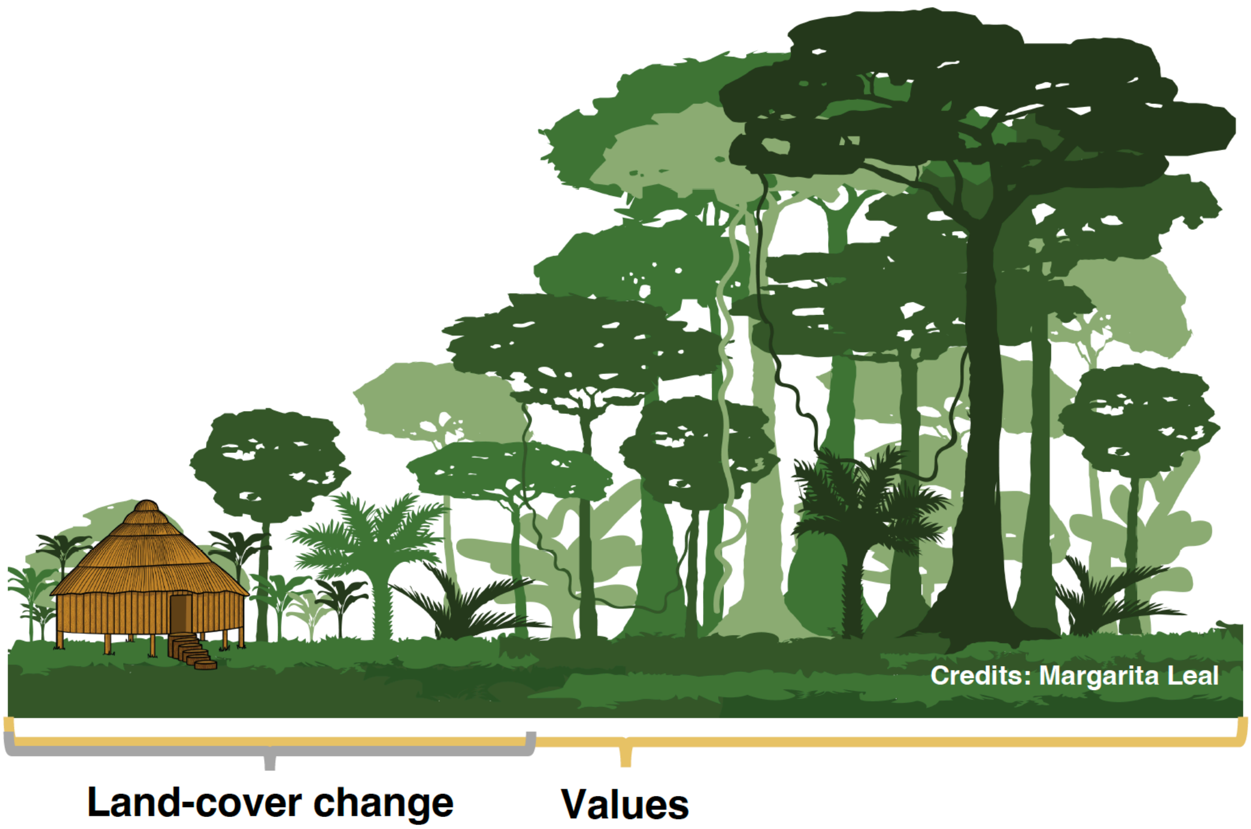

Figure 1. A visual summary of the results. Indigenous Peoples and Local Communities (IPLC) rely on concentrated and accessible areas for land use, mostly associated with food production, while other instrumental and relational values are dispersed across the landscape, contributing to the spatial and temporal stability of forest cover and carbon stocks.

Indigenous Peoples and Local Communities land use and forests' resilience

The spatial-temporal stability of IPLC land use, forest cover, and carbon stocks have relevant implications in terms of ecological resilience to different shocks. For instance, climate change has increased the frequency of droughts that bring severe consequences to forests' ecological functions (Bennett et al., 2015), reducing the availability of suitable habitats for species and impacting the reproductive strategies of pollinators and seed dispersers (Silva 2019). Moreover, droughts reduce aboveground carbon stocks through the increase in tree mortality and the reduction in tree growth rates (Hisano et al., 2018). All these effects can be exacerbated by forest fragmentation, which reduces forest carbon stocks by increasing lianas' over trees' abundances (Magnago et al., 2017). Fragmentation also causes the reduction and even the disappearance of trees with specialized pollination systems, supporting fewer pollinator populations (Girão et al., 2011).

Our findings show that IPLC land use results in a gradient of deforestation and forest disturbances that decline (Chapter 3), while carbon stocks (Chapters 1 and 2) increase inside forest patches, resulting in limited levels of fragmentation and creating heterogeneous landscapes that tend to be dominated by forests. This landscape heterogeneity favors structurally-complex forests that enhance forests' carbon stocks recovery (Ali et al., 2019). Moreover, Indigenous land use may diminish carbon stocks, especially in accessible areas, but it is known to preserve tree diversity (Mateo-Vega et al., 2019), which may potentially buffer the effects of drought (Esquivel-Muelbert et al., 2019) and climate change (Sakschewski et al., 2016). IPLC land use might also buffer the effects of fragmentation because forests dominate the landscapes and, thus, can maintain pollination and seed dispersal (Arroyo-Rodríguez et al., 2017). Consequently, IPLC management of the domestic forests could potentially maintain some resilience to climate change and forest fragmentation. Future studies could test IPLC domestic forests' resilience through remote sensing (Boulton et al., 2022) and landscape changes in functional diversity and ecosystem functioning (Esquivel-Muelbert et al., 2017).

The potential ecological resilience of IPLC domestic forests represents a form of sustainable landscape management. As explained above, my findings in Indigenous Lands (Chapters 1 and 3) and Community Managed PAs (Chapter 2) illustrate that land use changes, especially deforestation, tend to be concentrated near (< 5 km) land boundaries, settlements, and forest edges, moderately reducing carbon stocks. Despite this reduction, the carbon stocks on IPLC's accessible lands tend to be higher than those in the surroundings (Chapters 1 and 2). This concentrated land use seems mostly related to one instrumental value: food from agriculture (Chapter 3). Disturbances followed by recovery occur more than 5 km from land boundaries, settlements, and forest edges, resulting in smaller carbon stocks reductions than deforestation. The less disruptive forest disturbances are related to the extraction of timber and non-timber forest products (e.g., food gathering and household materials in Chapter 3). I also exhibit how cultural values regarding forests are spatially dispersed, and reach the most stable segments of forest landscapes, apparently limiting land use. The resulting heterogeneous landscape implies that the less disturbed segments of the domestic forests preserve multiple ecological functions, contributing to the sustainability of diverse instrumental and relational values across the landscape.

The diverse values, stability, and ecological resilience of IPLC domestic forests question previous studies assuming that inexorably IPLC land use will either expand into the forests or intensify to permanently replace natural forests (Terborgh & Peres, 2017). In other words, my findings oppose labeling IPLC domestic forests as increasingly deforested, disturbed, and, therefore, ecologically degraded. That is, lacking the capacity to recover and perform diverse ecological functions (Ghazoul & Chazdon, 2017). As one indigenous leader from the Amazon highlighted in a meeting with NGOs and scientists: "How could someone say our lands are degraded if they feed our people and provide clean air and water to everyone?". While numerous local case studies have characterized IPLC's landscape structures and its potential social and ecological long-term benefits (e.g., Berkes & Davidson-Hunt, 2006; Ramakrishnan, 1992; Toledo et al., 2003), my findings provide unambiguous support through quantitative assessments across diverse IPLC lands at the neotropical scale.

Policy challenges

Nevertheless, some well-established policy interventions affect IPLC domestic forests negatively. Across neotropical countries, governments have traditionally granted titles to private actors that make lands "productive" (Angelsen, 2010). This partially explains why in Central and South America land tenure security in private lands is associated with higher deforestation (Robinson et al., 2014). Additionally, in areas with a significant extent of natural forests, such as those inhabited by IPLC, there are economic incentives to deforest and then reforest with planted forests (Liscow, 2013; Walker, 2021). These economic incentives are exacerbated by land tenure insecurity. For example, economic incentives to title "productive lands" have encouraged colonist invasions in Indigenous Lands that, in some cases, are directly related to more than 60% of deforestation (Vergara-Asenjo et al., 2017). In Brazil, the economic incentives for deforestation are more direct: the government is dismantling environmental surveillance agencies and aims to regularize land grabbing, even inside Indigenous Lands (Conceição et al., 2021; Rorato et al., 2021). These perverse economic incentives clearly affect the stability of forest cover, carbon stocks, biodiversity, local livelihoods, and other values that emerge from the domestic forests. To avoid these adverse effects, some have suggested that titling lands accompanied by strict environmental restrictions can reduce deforestation (Pacheco & Meyer, 2022). Furthermore, Karsenty (2021) highlights that environmental incentives from global funds to developing countries should be conditioned to coherent policies that promote forest conservation, strengthen local rights, and prioritize investments related to IPLC.

Despite some policies' negative effects, other operating and proposed financial incentives may benefit IPLC domestic forests. REDD+ is one of those incentives initially envisioned as an international framework to compensate developing countries for reduced emissions primarily funded by carbon offsets (Agrawal et al., 2011). After the Paris Agreement, results-based payments from REDD+ became a critical component in mitigating climate change (Wong et al., 2016). Results-based payments aim to provide financial incentives to countries that reduce land use emissions relative to a benchmark (e.g., past forest reference emission levels) (UN-REDD Programme, 2015). However, only a few countries have received REDD+ results-based payments through a pilot program executed by UNFCCC's Green Climate Fund (Maniatis et al., 2019).

To date, REDD+ operation has been primarily based on local projects in voluntary carbon markets. Some of these projects have aimed to generate carbon credits through alliances between brokers (NGOs or private companies) and communities, such as the forest communities from Petén (Guatemala) (Chapter 2, Hodgdon et al., 2013), the Brazil nut producers federation in Madre de Dios (Peru), and the Shipibo, Conibo, and Cacataibo indigenous communities in Ucayali (Peru) (Sills et al., 2014; Sunderlin et al., 2015). Overall, Coutiño (2022) suggested that these kinds of REDD+ local projects with certified carbon monitoring have resulted in net avoided emissions from deforestation and degradation in tropical countries. Hence, local REDD+ projects could represent an opportunity for IPLC to receive compensations for avoided land use emissions without the intervention of governments. Nevertheless, their potential success has been questioned due to a lack of transparent benefit-sharing schemes for IPLC (Sills et al., 2014; Sunderlin et al., 2015) and the possibility of jeopardizing their land tenure security (Karsenty et al., 2014).

Other REDD+ initiatives can be defined as nested because they aim to articulate international donors, national and subnational governments, and local projects (Pedroni et al., 2009). For example, Guyana's government proposed to the UNFCCC a results-based mechanism where indigenous communities will be compensated annually in terms of the difference between national and local forest reference emission levels and their carbon stocks in the previous year (Overman et al., 2018). There are no direct cash transfers, and the benefits are expected to be invested in infrastructure, health, and education for communities. Similarly, the case of ISA-Carbono in Acre (Brazil) (Chapter 2) articulates international donors, a subnational government, and Local Communities, including those in Community Managed PAs, which receive financial incentives for sustainable development activities. Both Guyana's government proposal and ISA-Carbono in Acre represent a type of REDD+ initiative that has become multi-objective (i.e., poverty alleviation, biodiversity, and indigenous rights), financially dependent on international aid and does not translate into results-based payments for countries or local stakeholders (Angelsen, 2017).

The shift away from results-based payments is evident in other programs. "Bolsa Floresta" in Brazil is a mechanism that articulates international donors, the private sector, and national and subnational governments to compensate IPLC following specific rules, such as zero net deforestation and sending children to school (Sills et al., 2014; Sunderlin et al., 2015). Participating families receive cash transfers and support for income-generating activities, education, and health. Some studies have suggested that this kind of flat-rate payment scheme could be applied as a mechanism to redistribute national and subnational REDD+ revenues to IPLC (Skutsch et al., 2011; Torres & Skutsch, 2012). Compared with the voluntary local REDD+ projects that generate carbon credits, nested initiatives do not have a standard financial mechanism to transfer benefits to IPLC. Additionally, their dependence on international donors questions their financial sustainability in the future. In any case, the most significant potential of nested initiatives relies on their capacity to obtain broad financial resources that can ideally be distributed to IPLC on a national or subnational scale.

REDD+ key activities also include the conservation and enhancement of carbon stocks (Wong et al., 2016). However, REDD+ incentives are focalized on avoided land use emissions based on forest reference levels (e.g., past reference periods or business-as-usual scenarios), frequently resulting in larger financial benefits for those countries (or recipients) with low remaining forest cover and high historical levels of deforestation (Miles & Kapos, 2008). Because of the lack of clear incentives for conserving forests' carbon stocks, Funk et al. (2019) suggest a diversified portfolio for REDD+, which balances high-yield/high-risk investments in threatened forests with low-yield/low-risk investments. This diversified portfolio could result in a dual payment stream for conserving forests and maintaining stable carbon stocks, such as those in IPLC domestic forests. In summary, the voluntary local REDD+ projects and nested REDD+ initiatives exhibit numerous operating pathways to provide financial incentives to the IPLC that avoid land use emissions. To date, REDD+ mechanisms for explicitly rewarding the conservation and stability of carbon stocks are largely hypothetical.

Besides REDD+, there are other incentives for stable forests and carbon stocks. For instance, the Ecological Fiscal Transfers (EFTs) are designed to transfer public revenues vertically between government levels (e.g., national to municipality) or horizontally within the same government levels (e.g., provinces) (Busch et al., 2021). In Brazil, some states have transferred revenues to municipalities based on the land area under protection, Indigenous Lands, and forest area (Lima et al., 2020). Similarly, India's national government transfer revenues to states based on forest density (Busch & Mukherjee, 2018). EFTs redistribute countries' revenues among jurisdictions that have refrained from revenue-generating activities, such as industries and agriculture (Busch et al., 2021). Such transfer implies a recognition of the diverse benefits that can derive from standing forests. Following this rationale, it has been suggested that countries clearly account for forests' carbon stocks and flows, ecological integrity, and multiple benefits to people to demonstrate the value and secure funding for maintaining stable forests (Dooley et al., 2022).

The lack of policy incentives for IPLC in domestic forests highlights some policy-science gaps that deserve further investigation. To date, the scientific literature, including Chapter 1 and Chapter 2, has focused on the effect of IPLC with customary or established tenure rights in forest conservation (e.g. Blackman et al., 2017; Bonilla-Mejía & Higuera-Mendieta, 2019; Moon et al., 2019; Nelson & Chomitz, 2011; Nolte et al., 2013; Sze et al., 2022), rather less attention has been paid to how forest conservation changes after granting land tenure rights, especially in the long-term (Tseng et al., 2021). As explained above, clear tenure rights play a relevant role in establishing and distributing incentives among IPLC. Future studies should compare the spatial-temporal effects before and after granting land tenure rights in deforestation, disturbance, carbon stocks, biodiversity, and values regarding nature. Moreover, the second chapter provided insights regarding the simultaneous influence of land tenure rights along with additional incentives in the form of local and subnational REDD+ projects in Petén (Guatemala) and Acre (Brazil). However, further studies are needed on the national and neotropical scale to reveal if these simultaneous policy interventions contribute to climate change mitigation and biodiversity conservation. Finally, there is a limited understanding of which indicators might be suitable to evaluate the effectiveness of interventions to mitigate the effects of climate change and conserve biodiversity (Seddon et al., 2020). In addition to forest cover or carbon stocks, future studies need to explore other indicators related to social well-being (e.g., education, health, food security, cultural identity, and social cohesion). Finally, there is a pressing need to explore potential evaluation mechanisms and policies that may reward the stability of forests and carbon stocks (e.g., UN, 2021).

Conclusion and Summary

Given IPLC domestic forests' potential contribution to climate change mitigation, biodiversity conservation, and other nature’s contributions to people, this thesis aimed to answer the question: how do land tenure, policy incentives, and values regarding nature influence domestic forests’ stability and carbon stocks in the neotropics? Regarding land tenure, Chapter 1 shows that Indigenous Lands, including their overlaps with Protected Areas, secure higher and more stable carbon stocks than Other Lands (i.e., private/public lands without protection) and are as effective in protecting carbon as non-overlapping Protected Areas (PAs) in Panama and the Amazon Basin portions of Ecuador, Peru, Colombia, and Brazil. Similarly, forest communities in Petén (Guatemala) and rubber tappers in Acre (Brazil) that were granted the management of PAs were found to effectively maintain carbon stocks, even relative to other categories of PAs. After REDD+ was implemented (i.e., policy incentive), these Community Managed PAs resulted in avoided land use emissions and did not display leakage. Based on the carbon stocks dynamics in these IPLC lands and using as a case study three Indigenous Lands from eastern Panama, Chapter 3 exhibited that the spatial-temporal stability of indigenous land use and, thus, forest cover, was linked to a worldview that integrates diverse instrumental and relational values regarding nature to manage landscapes. This spatial-temporal stability of carbon stocks and forest cover demonstrates that IPLC's forest management in the neotropical domestic forests represents a cornerstone in climate change mitigation, forest conservation, social wellbeing, and other values regarding nature.

The paucity of operating policy interventions related to IPLC domestic forests suggests the need for equitable pathways for countries in the global south to reduce carbon emissions, protect forests, and, thus, comply with international commitments related to climate change and biodiversity. Building equitable pathways requires the assessment of current policy interventions related to land tenure rights and financial incentives in IPLC domestic forests to designing effective rewards for forest stability. Any future policy intervention for forest stability should consider that IPLC domestic forests nurture a diverse set of instrumental and relational values intertwined with complex realities. Hence, any potential natural climate solution in IPLC domestic forests must acknowledge, respect, and empower local worldviews, governance systems, livelihoods, and cultural identities. Additionally, land tenure insecurity, food insecurity, and precarious access to health and education are not only a constraint for climate change mitigation; they are a pressing urgency as the climate change crisis. Finally, climate change mitigation in the domestic forests and other land-based solutions cannot be considered as standalone interventions for mitigating the effects of climate change but an addition to the necessary reduction of fossil fuel emissions (Matthews et al., 2022).

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Supplementary Material

Chapter 1: Supplementary Material

S1 Appendix. Geospatial information and covariates
Table A. Geospatial Information and its sources by country.

Country	Geospatial Information	Source
All countries	Annual carbon density (2003 – 2016)	Woods Hole Research Center (Baccini et al., 2012; Baccini et al., 2017).
All countries	Elevation and slope	Shuttle Radar Topographic Mission – USGS (United States Geological Survey)
Panama	Roads, human settlements (> 5000 inhabitants)*, rivers, PAs.	STRI ("Smithsonian Tropical Research Institute").
Panama	Titled and claimed ITs	Neotropical Ecology Laboratory (Prof. Catherin Potvin McGill University/STRI), COONAPIP (Coordinadora Nacional de los Pueblos Indígenas de Panamá).
Amazon Basin (Colombia, Ecuador, Perú, Brasil).	PAs and ITs, roads	RAISG (Red Amazónica de Información Socio-Ambiental Geo-Referenciada).
Colombia	Rivers	IGAC ("Instituto Geográfico Agustín Codazzi").
Colombia	Human settlements (> 5000 inhabitants)*	DANE (Departamento Administrativo Nacional de Estadística).
Ecuador	Human settlements (> 10 000 inhabitants)*, Rivers.	IGM ("Instituto Geográfico Militar").
Peru	Rivers	IGN ("Instituto Geográfico Nacional").
Peru	Human settlements (> 5000 inhabitants)*	INEI ("Instituto Nacional de Estadística e Informática") and Ministry of Education.
Brazil	Human settlements (> 5000 inhabitants)*, Rivers.	IBGE ("Instituto Brasileiro de Geografía e estadística").

* The human settlements shown in the S4C Appendix includes locations with less than 5000 inhabitants.

Table B. Covariates mean differences between PAs, ITs, and OAs with other lands by country and their statistical significance from Mann Whitney U tests.

Country	Land tenure	Roads (km)	Settlements (km)	Rivers (km)	Elevation (m)	Slope (%)
Panama	PAs	-25.91***	-6.04***	-0.23***	213.00***	-2.00***
	ITs	-52.36***	-8.20***	-0.33***	-154.00***	-2.00***
	OAs	-109.12***	-13.86***	-0.01***	-3.00***	-3.00***
Colombia	PAs	-29.10***	-37.56***	-0.25***	12.00***	0.00***
	ITs	-13.92***	-62.62***	0.16*	177.00*	1.00*
	OAs	-28.87***	-70.74***	1.07***	186.00***	1.00***
Ecuador	PAs	-12.50***	-8.66***	-0.53***	-309.00***	-2.00***
	ITs	-28.49***	-16.21***	0.04***	415.00***	3.00***
	OAs	-23.36***	-25.11***	-0.13***	447.00***	3.00***
Peru	PAs	-28.05***	-46.95***	-0.04***	-22.00***	0.00***
	ITs	2.06***	5.07***	2.08***	29.00***	0.00***
	OAs	-29.54***	3.26***	-2.85***	235.00***	2.00***
Brazi	PAs	-27.22***	-33.14***	-3.54***	9.00***	0.00***
	ITs	-32.17***	-91.69***	-7.91***	-53.00***	0.00***
	OAs	-15.65***	-126.83***	-15.65***	-49.00***	-1.00***

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Table C. Coarsening Choices applied through Coarsened Exact Matching (CEM) by country across PAs, ITs, and OAs.

Country	Land tenure	Roads (km)	Settlements (km)	Rivers (km)	Elevation (m)	Slope (%)
Panama	PAs	0.5	0.5	0.5	50	1
	ITs	2.5	2	1	100	1.5
	OAs	1	2	1	150	1.5
Colombia	PAs	1	1	0.5	50	1.5
	ITs	2	1	1	50	1.5
	Overlapped Areas	2	2	1	100	1.5
Ecuador	PAs	1	1	1	50	2
	ITs	1	2	0.8	150	2
	OAs	0.5	2	0.7	150	2
Peru	PAs	2	1	2.5	200	2
	ITs	1	1	1	150	2
	OAs	1	1	1	150	2
Brazil	PAs	1	1	1	100	1
	ITs	1	1	1	200	1.5
	OAs	1	1	1	200	1.5

S2 Appendix. Covariate balance statistics and falsification tests.

Fig A. Covariates standard mean differences between ITs, OAs, and PAs with other lands before (Pre-Match) and after matching analysis (Matched) across neotropical countries.

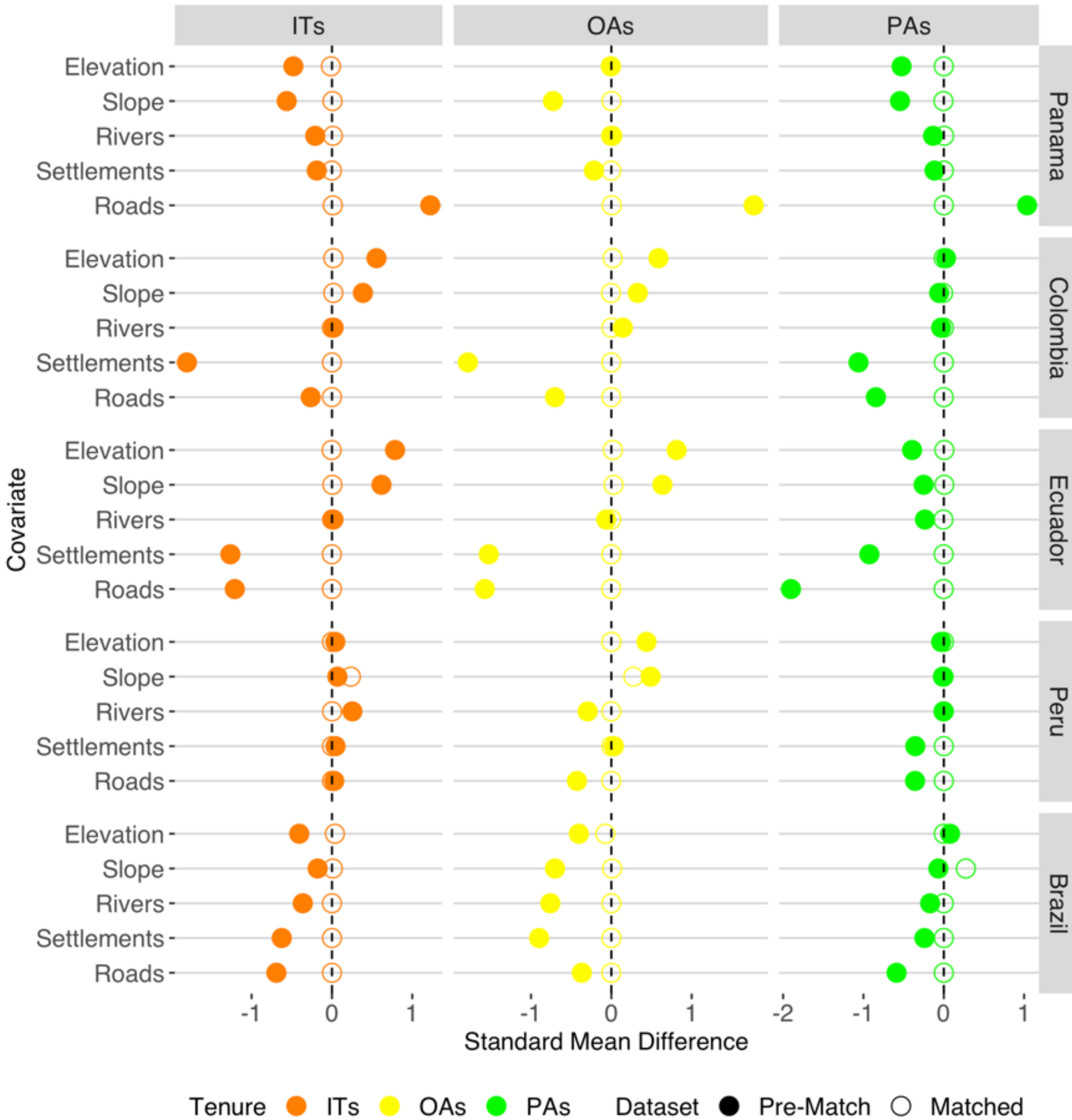


Fig B. Kolmogorov-Smirnov statistics of covariates between ITs, OAs, and PAs with other lands before (Pre-Match) and after matching analysis (Matched) in neotropical countries.

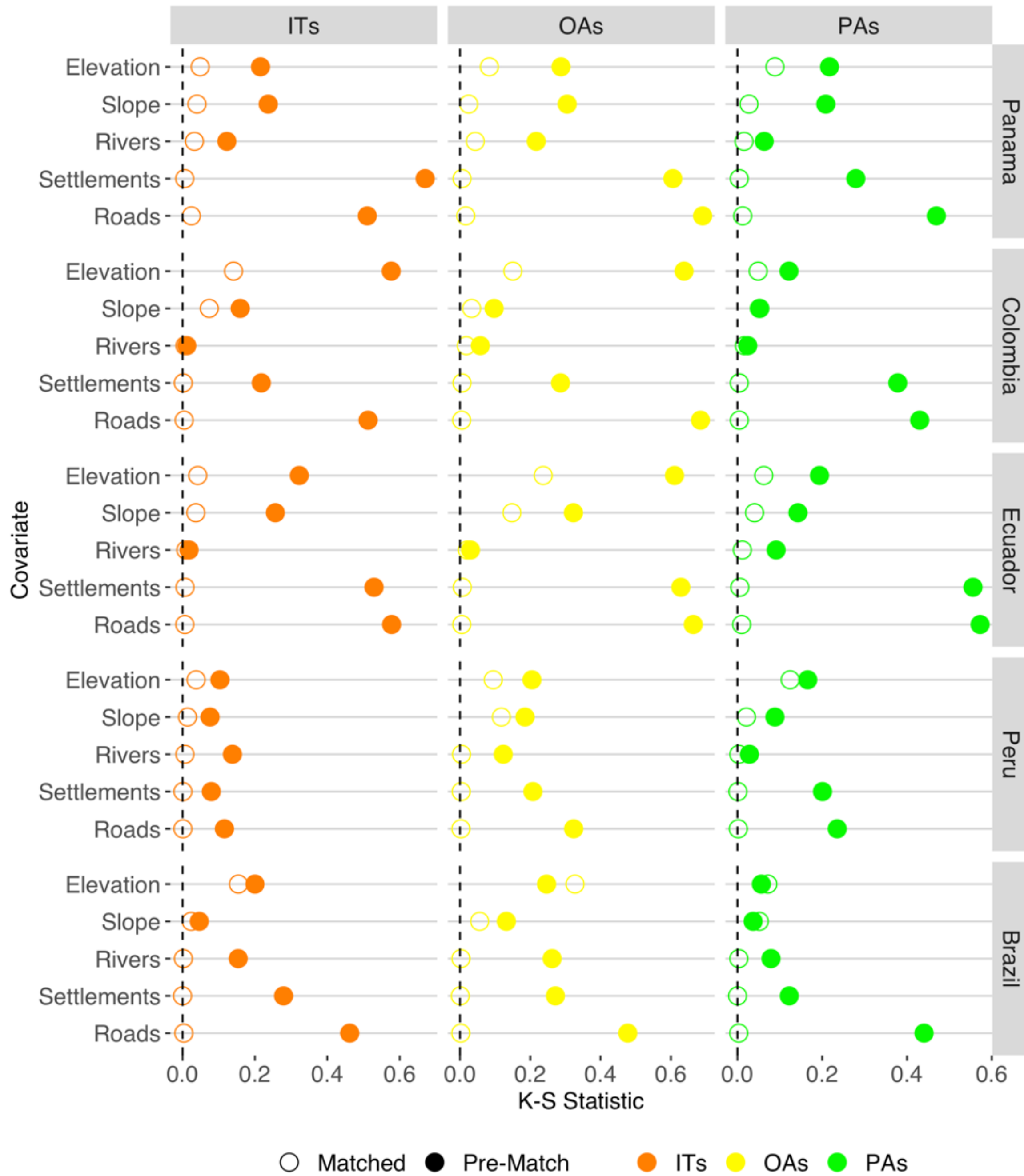


Fig C. Covariate standard mean differences before (Pre-Match) and after matching (Matched) in geographic discontinuity designs across the boundaries of ITs, OAs and PAs in neotropical countries.

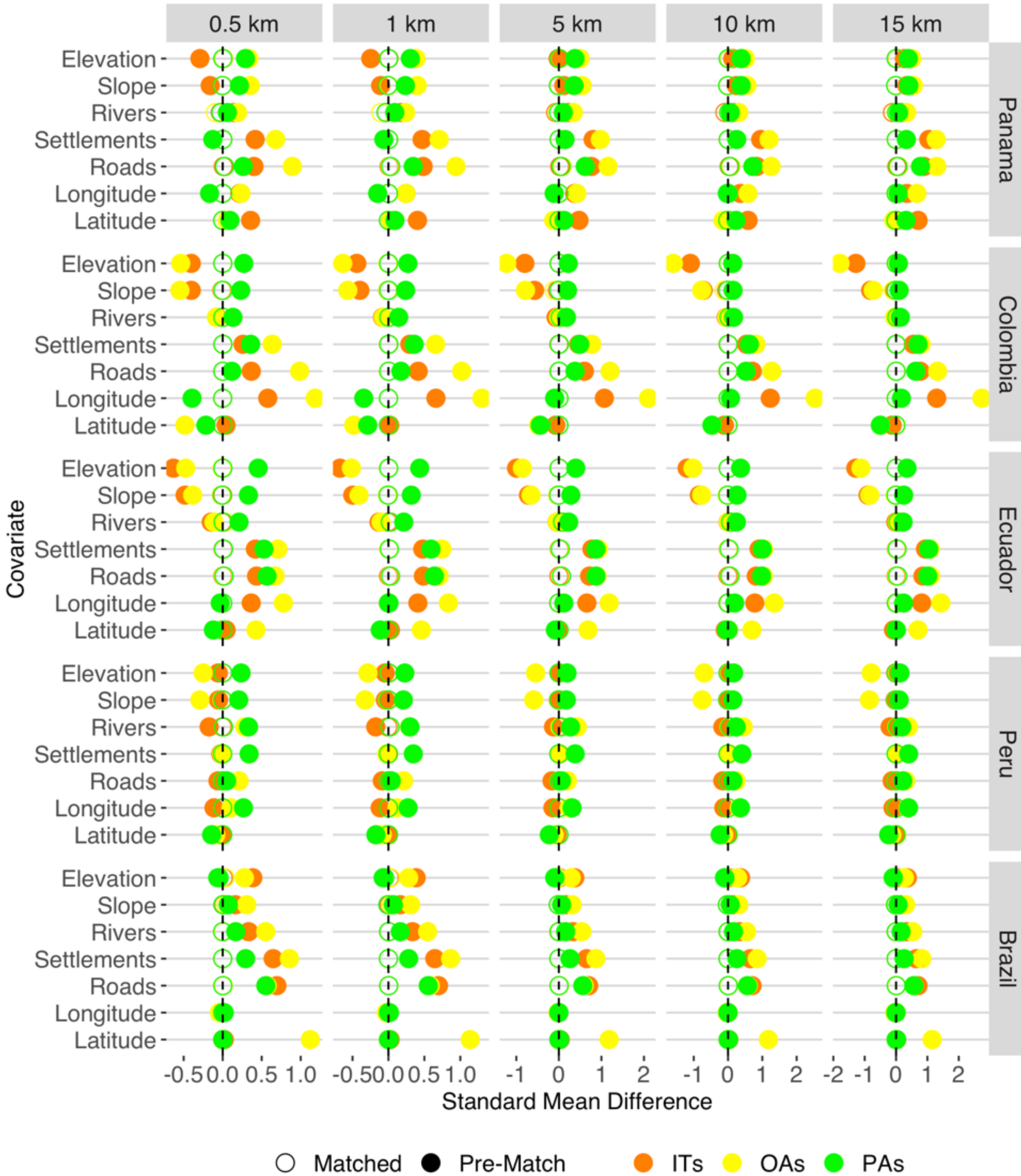


Fig D. Kolmogorov-Smirnov statistics of covariates before (Pre-Match) and after matching (Matched) in geographic discontinuity designs across the boundaries of ITs, OAs and PAs in neotropical countries.

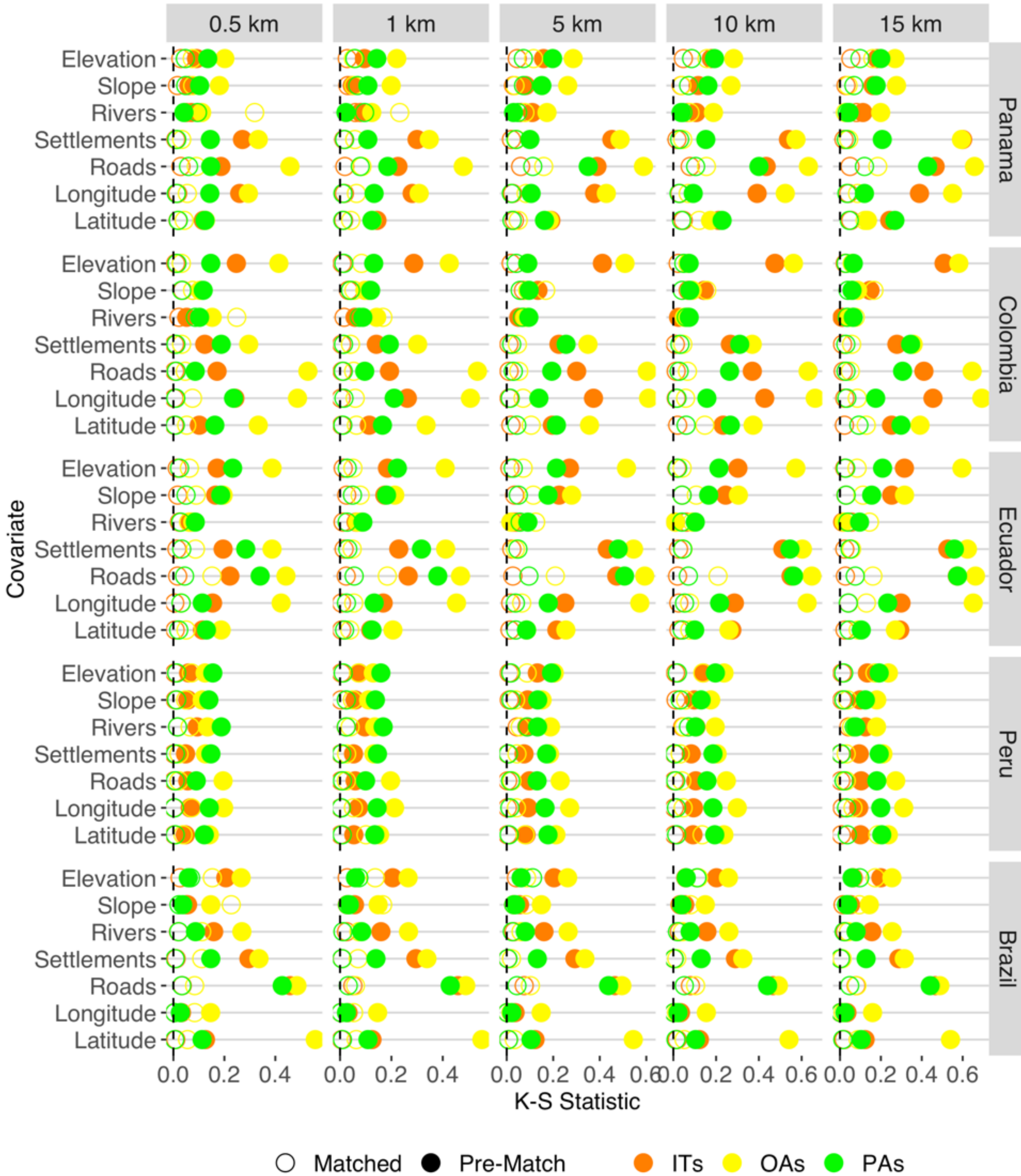
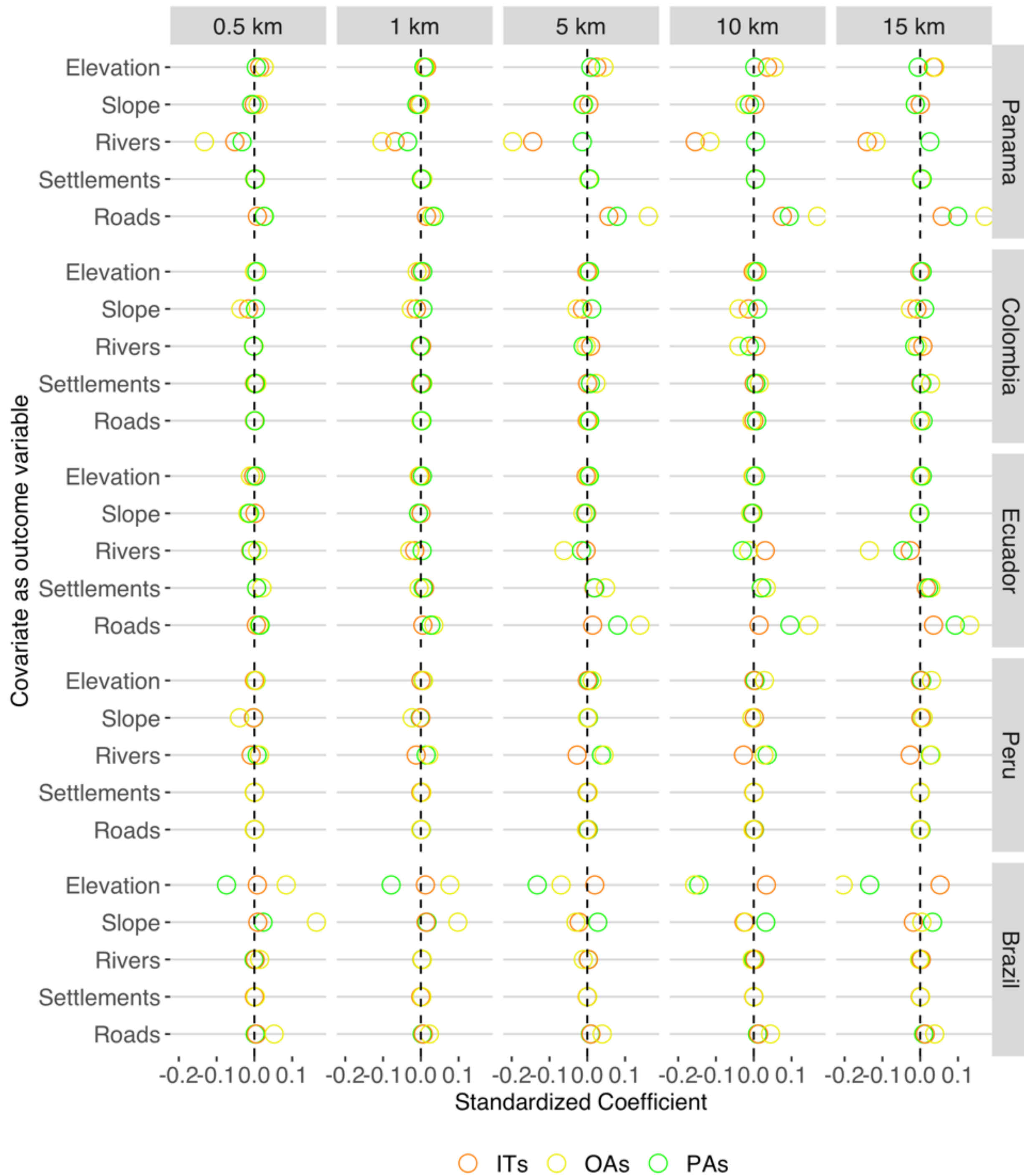
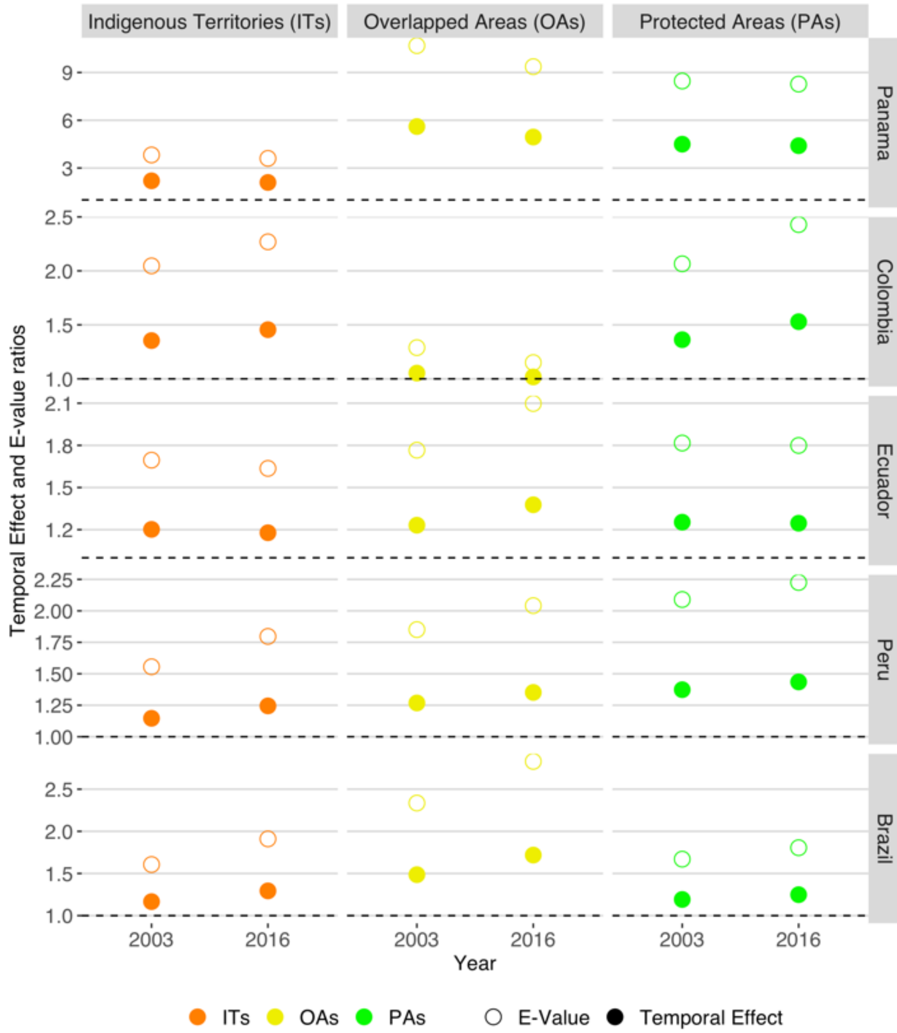


Fig E. Covariate falsification tests derived from linear mixed models in geographic discontinuity designs across the boundaries of ITs, OAs and PAs in neotropical countries.



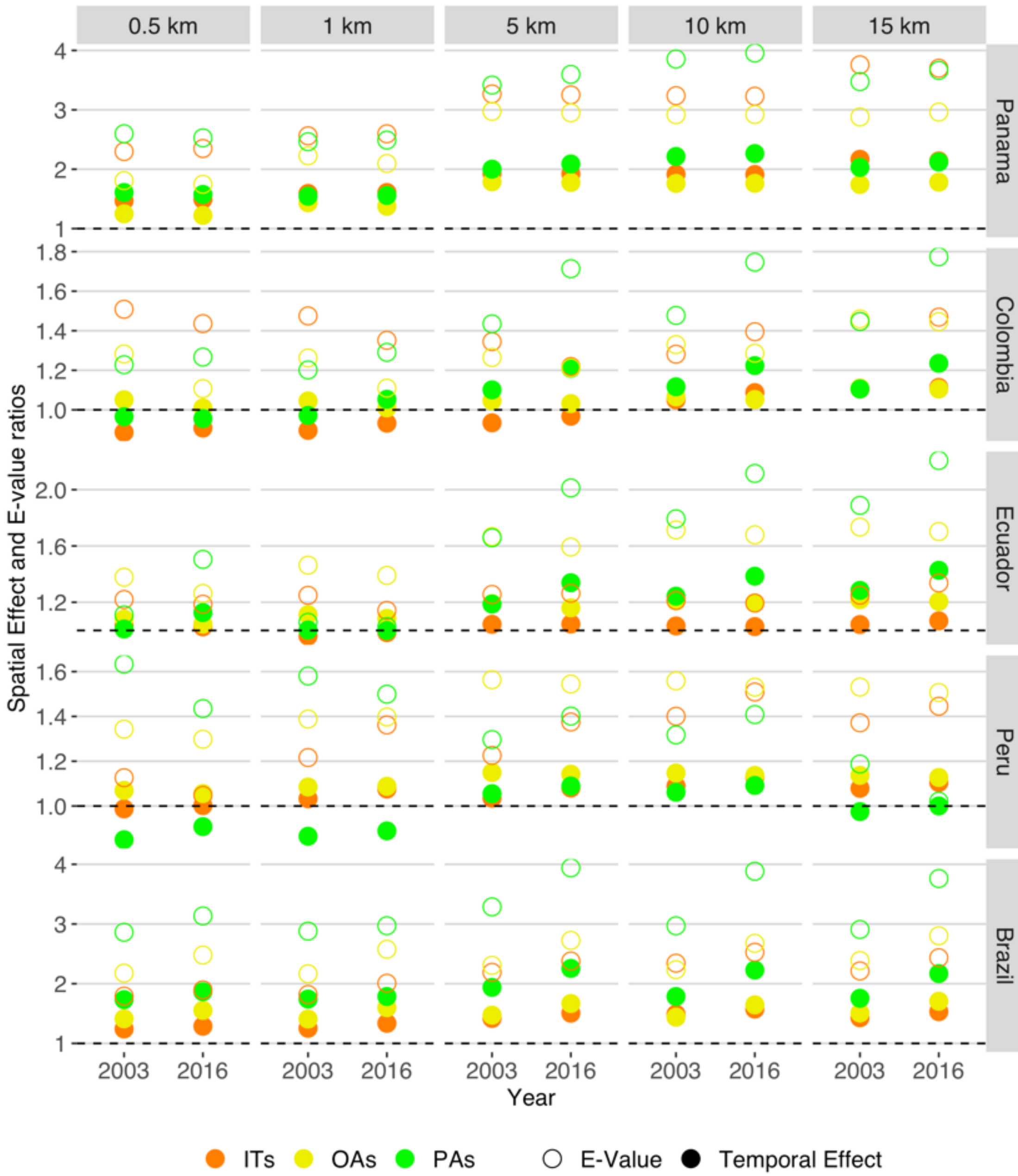
S3 Appendix. Sensitivity Analyses.

Fig A. Sensitivity analysis in the temporal effects of ITs, OAs, and PAs on carbon stocks in 2003 and 2016 across neotropical countries.



The temporal effect ratio is equivalent to the probability of a positive temporal effect in the treatment (i.e., ITs, OAs, and PAs) divided by the probability of a positive temporal effect in the control (other lands). The E-value represents the minimum strength that an unmeasured covariate would need to have with the treatment (i.e., ITs, OAs, PAs) and their temporal effect, for the treatments and temporal effect association not to be causal.

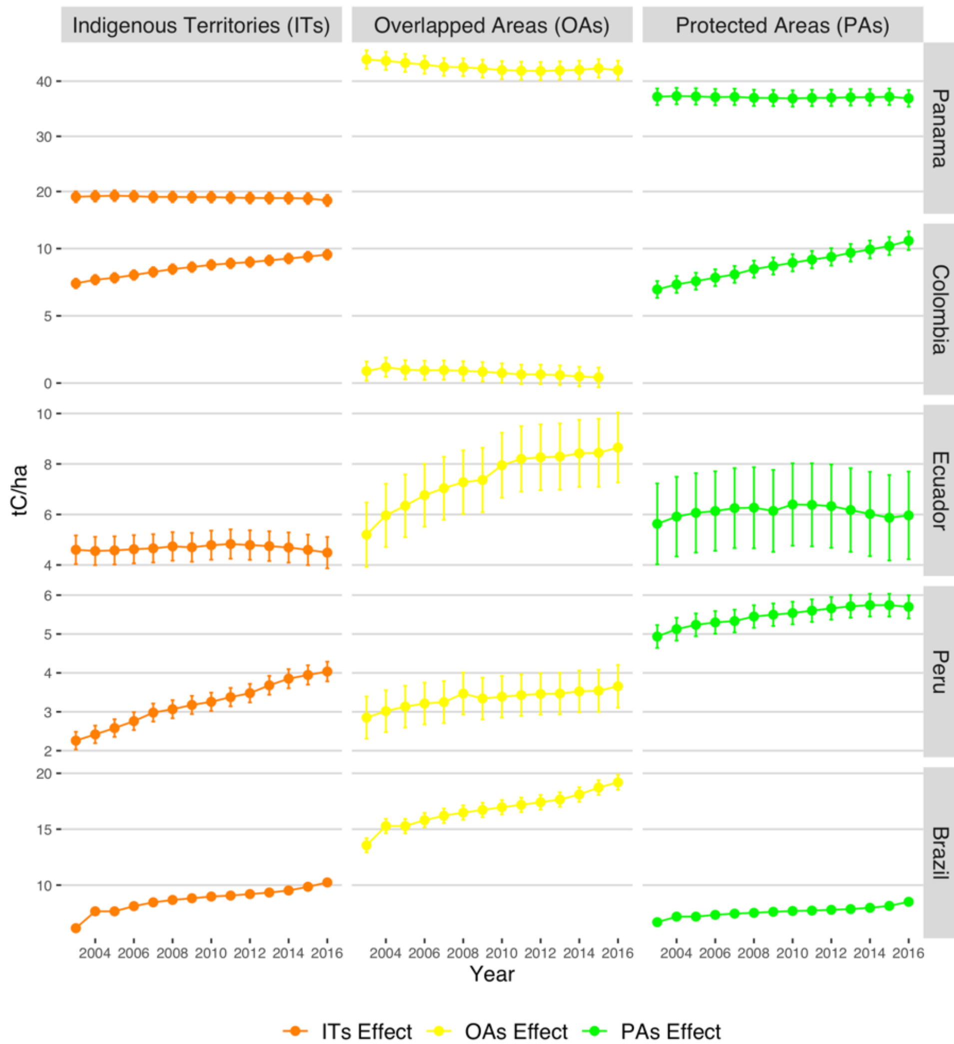
Fig B. Sensitivity analysis in the spatial effects of ITs', OAs', and PAs' boundaries on carbon stocks in 2003 and 2016 across neotropical countries.



The spatial effect ratio is equivalent to the probability of a positive spatial effect in the treatment (i.e., ITs, OAs, and PAs) divided by the probability of a positive spatial effect in the control (other lands). The E-value represents the minimum strength that an unmeasured covariate would need to have with the treatment (i.e., ITs, OAs, PAs) and their spatial effect, for the treatments and spatial effect association not to be causal.

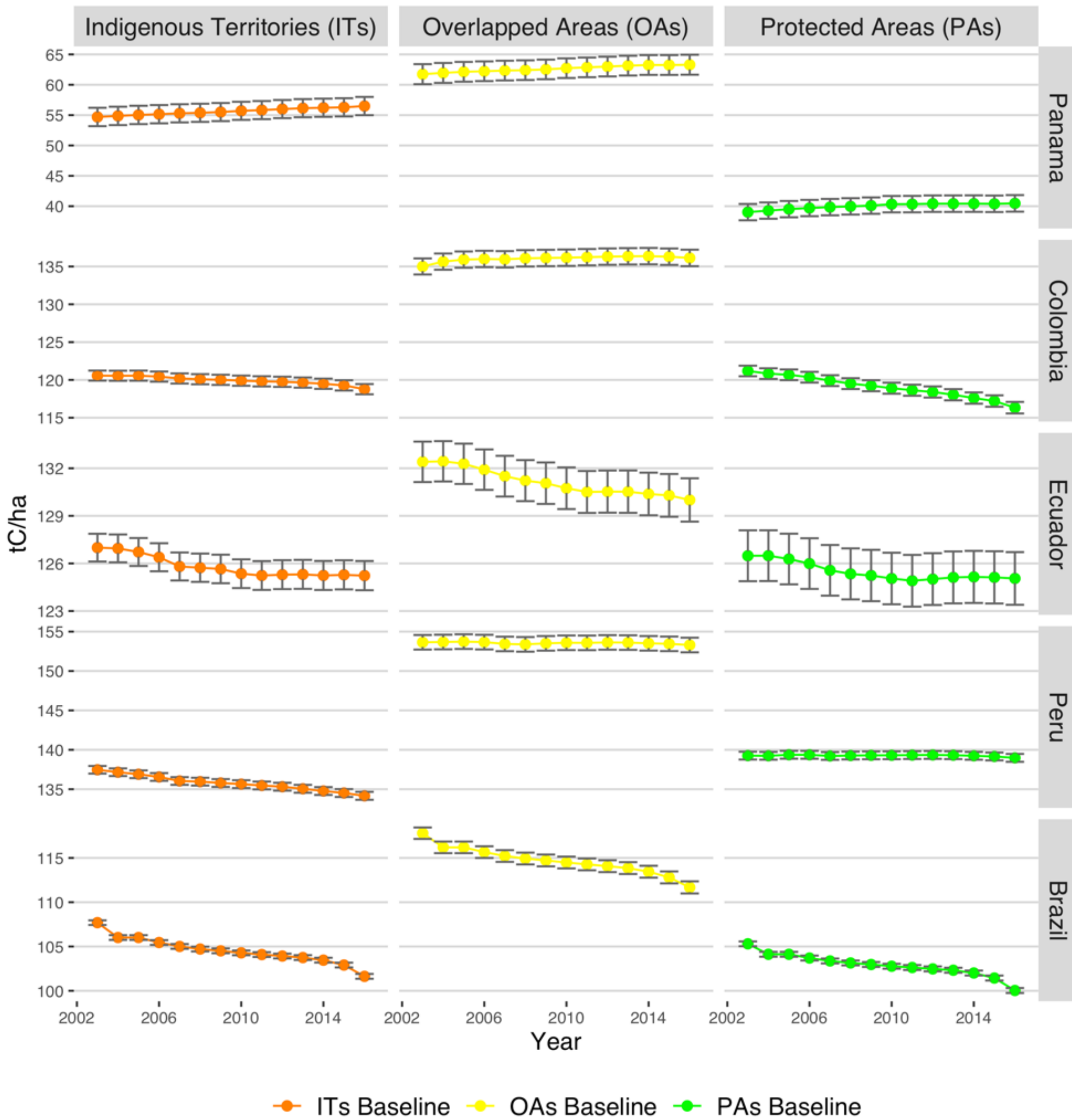
S4 Appendix. Temporal effects, carbon baselines, and human settlements distribution.

Fig A. The temporal effect of ITs, OAs, and PAs on carbon stocks between 2003 and 2016 across neotropical countries.



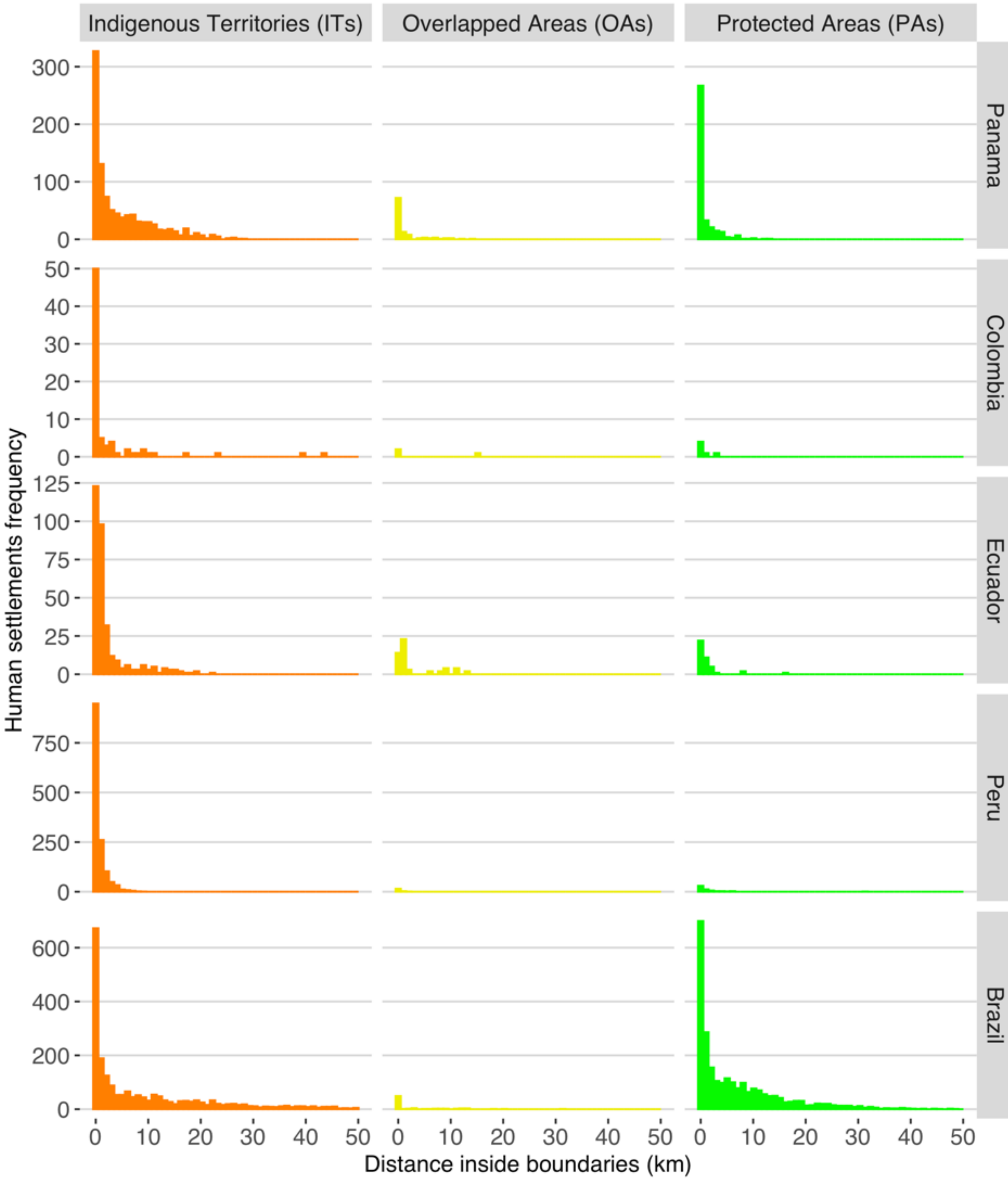
Each point are the significant annual effects ($p < 0.05$) of ITs (orange), OAs (yellow), and PAs (green) on carbon stocks. The temporal effects represent the annual differences of carbon stocks between ITs, OAs, and PAs with other lands after controlling for the spatial location through matching analysis and linear mixed models. Error bars reflect 95% confidence intervals for the temporal effect derived from the linear mixed models.

Fig B. The carbon stocks baseline of ITs', OAs', and PAs' temporal effects across neotropical countries.



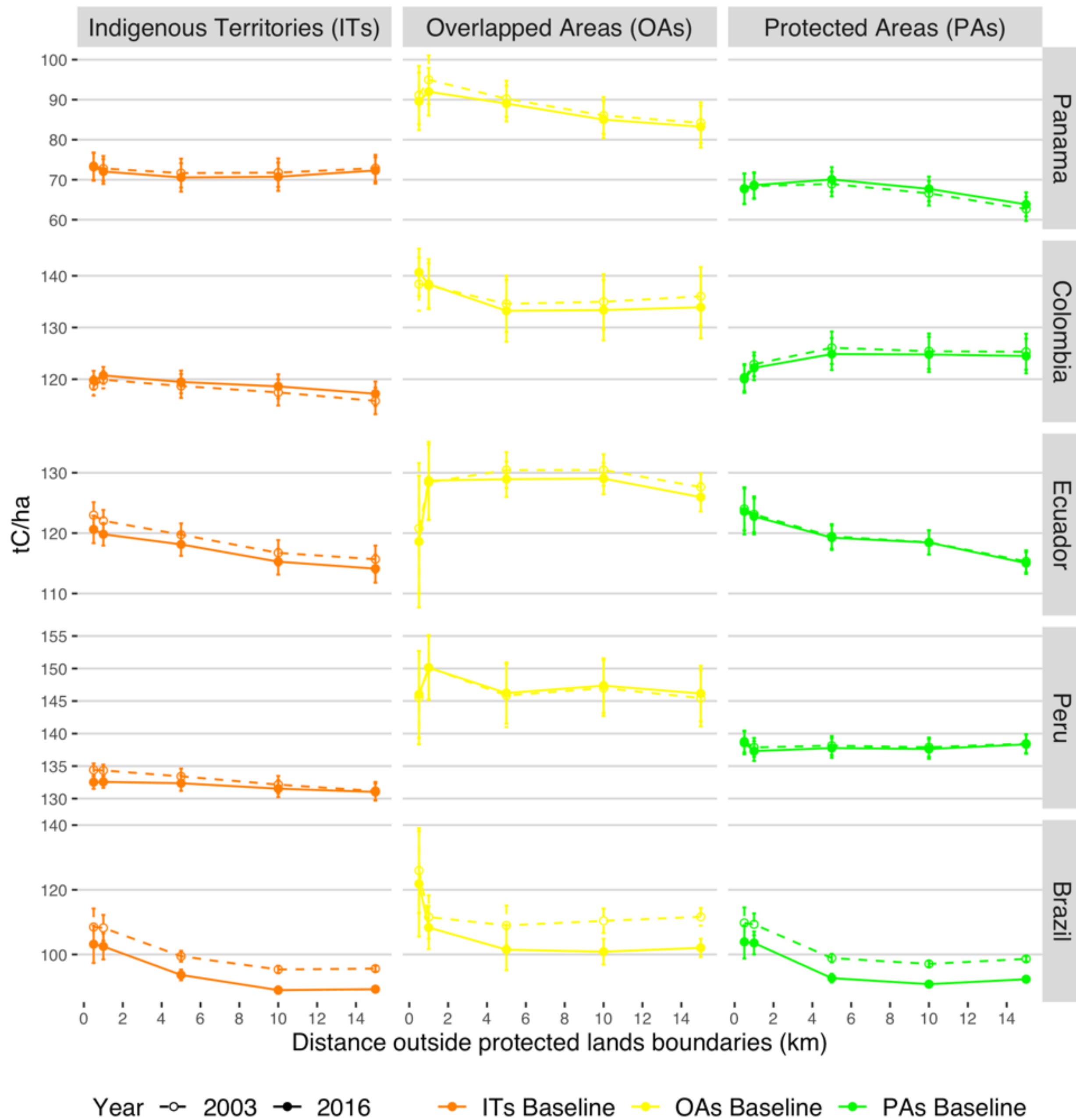
Each point represents the mean annual carbon stocks found in other lands (i.e., carbon stocks baseline) that share spatial location covariates with ITs (orange), OAs (yellow), and PAs (green) after matching analysis and linear mixed models. Error bars reflect 95% confidence intervals for the carbon stocks baselines derived from the linear mixed models.

Fig C. Distribution of human settlements inside the boundaries of ITs, OAs, and PAs across neotropical countries.



The human settlements included are those registered by national institutions in Amazon Basin countries and STRI in Panama. Data sources are shown in the S1 Appendix.

Fig D. The carbon stocks baseline outside the boundaries of ITs, OAs, and PAs across neotropical countries.



Full (2016) or empty (2003) points represent the mean annual carbon stocks found in other lands (i.e., carbon stocks baseline) outside the boundaries of ITs (orange), OAs (yellow), and PAs (green) at a certain buffer distance. Error bars reflect 95% confidence intervals for the carbon stocks baselines derived from linear mixed models.

Chapter 2: Supplementary Material

Supplementary Tables

Jurisdiction	Land tenure	2003	SD	2007	SD	2011	SD	2015	SD
Acre (Brazil)	Other Lands	131.15	49.71	128.14	51.55	127.18	52.01	126.27	52.52
	Strict PAs	160.17	9.53	160.56	9.13	160.59	9.08	160.50	8.95
	Community Managed PAs	153.75	16.36	153.61	17.42	153.80	18.13	153.75	19.43
	Sustainable Use PAs	126.18	48.36	121.93	50.52	120.43	51.16	118.89	51.94
Petén (Guatemala)	Other Lands	50.55	21.99	46.39	22.13	44.58	22.72	45.13	23.00
	Strict PAs	65.44	23.62	62.11	24.20	60.71	25.35	61.08	26.56
	Community Managed PAs	78.50	14.20	80.89	13.62	81.92	13.95	82.94	14.65
	Sustainable Use PAs	68.69	22.48	66.00	22.27	63.55	23.36	61.71	24.95

Table S1. Mean annual carbon stocks across (tC/ha) land tenures in Acre (Brazil) and Petén (Guatemala). SD is the standard deviation of the mean.

Jurisdiction	Land tenure	Slope (°)	SD	Elevation (m)	SD	Temperature (c°/year)	SD	Precipitation (mm/year)	SD
Acre (Brazil)	Other Lands	0.79	0.47	227.44	42.27	254.72	3.71	1969.77	153.60
	Strict PAs	0.82	0.78	269.17	37.86	253.57	3.52	1982.06	201.45
	Community Managed PAs	0.78	0.44	254.21	39.28	252.28	3.81	1861.31	120.69
	Sustainable Use PAs	0.75	0.47	216.76	40.25	254.54	4.63	1947.82	145.73
Petén (Guatemala)	Other Lands	1.29	1.24	221.19	96.05	247.03	6.03	1976.49	370.70
	Strict PAs	1.39	1.72	198.75	126.90	252.62	8.68	1751.12	331.90
	Community Managed PAs	1.13	1.16	213.60	54.85	253.17	3.79	1344.99	94.73
	Sustainable Use PAs	1.38	1.65	228.91	172.78	251.92	10.79	1598.24	319.10

Table S2. Mean values for agriculture suitability covariates before matching analysis across land tenures in Acre (Brazil) and Petén (Guatemala). SD is the standard deviation of the mean.

Jurisdiction	Land tenure	2002 (people /km2)	SD	2007 (people /km2)	SD	2011 (people /km2)	SD	2000 (min)	SD	2015 (min)	SD
Acre (Brazil)	Other Lands	8.77	149.23	10.09	170.53	11.18	188.21	1297.42	1371.87	805.42	885.88
	Strict PAs	0.12	0.65	0.15	0.75	0.17	0.88	2145.56	913.89	1511.64	768.73
	Community Managed PAs	0.44	3.13	0.54	4.33	0.62	4.93	2325.12	1771.67	1057.25	692.22
	Sustainable Use PAs	2.85	41.32	3.18	46.86	3.44	50.99	1041.32	1052.88	513.15	573.62
Petén (Guatemala)	Other Lands	22.82	69.79	28.16	93.67	32.53	114.47	527.13	215.87	141.30	74.24
	Strict PAs	10.74	20.37	12.70	27.12	14.59	34.10	825.14	485.43	387.76	226.28
	Community Managed PAs	2.53	1.62	2.53	1.47	2.96	1.38	573.95	225.04	552.85	245.75
	Sustainable Use PAs	7.59	12.69	8.64	16.51	9.91	17.92	800.66	529.12	387.29	212.44

Table S3. Mean values for market access covariates before matching analysis across land tenures in Acre (Brazil) and Petén (Guatemala). Population density is measured as the number of people per km^2. Travel distance to the nearest city is measured in minutes (min). SD is the standard deviation of the mean.

Supplementary Figures

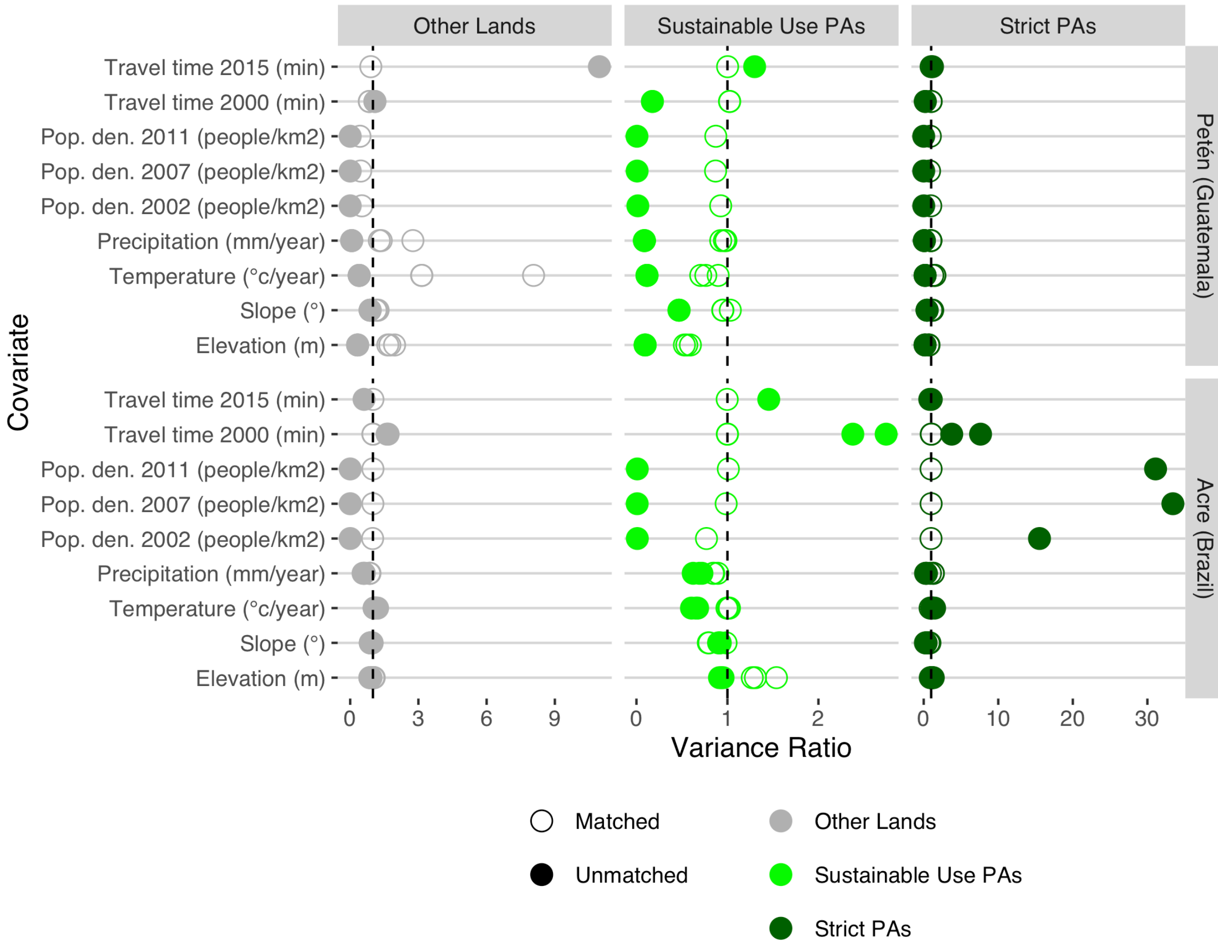


Figure S1. Covariates' variance ratios between Community Managed PAs and Other Lands, Sustainable Use PAs, and Strict PAs before (Unmatched) and after matching analysis (Matched) in the Petén (Guatemala) and Acre (Brazil).

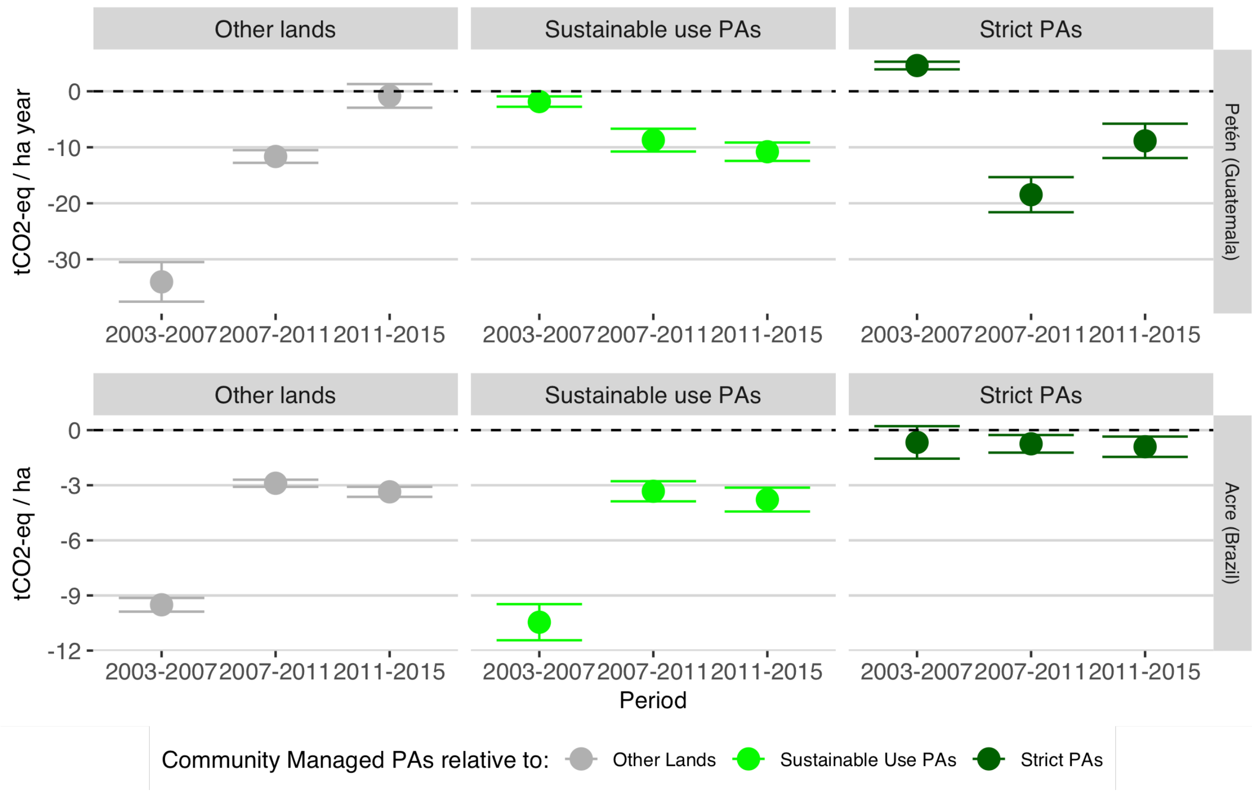


Figure S2. Net carbon changes of Community Managed PAs' counterfactuals in Petén (Guatemala) and Acre (Brazil) after controlling for covariates. Negative carbon changes ($p < 0.05$) indicate net carbon emissions compared to Community Managed PAs. Error bars indicate 95% confidence intervals for the net carbon changes.

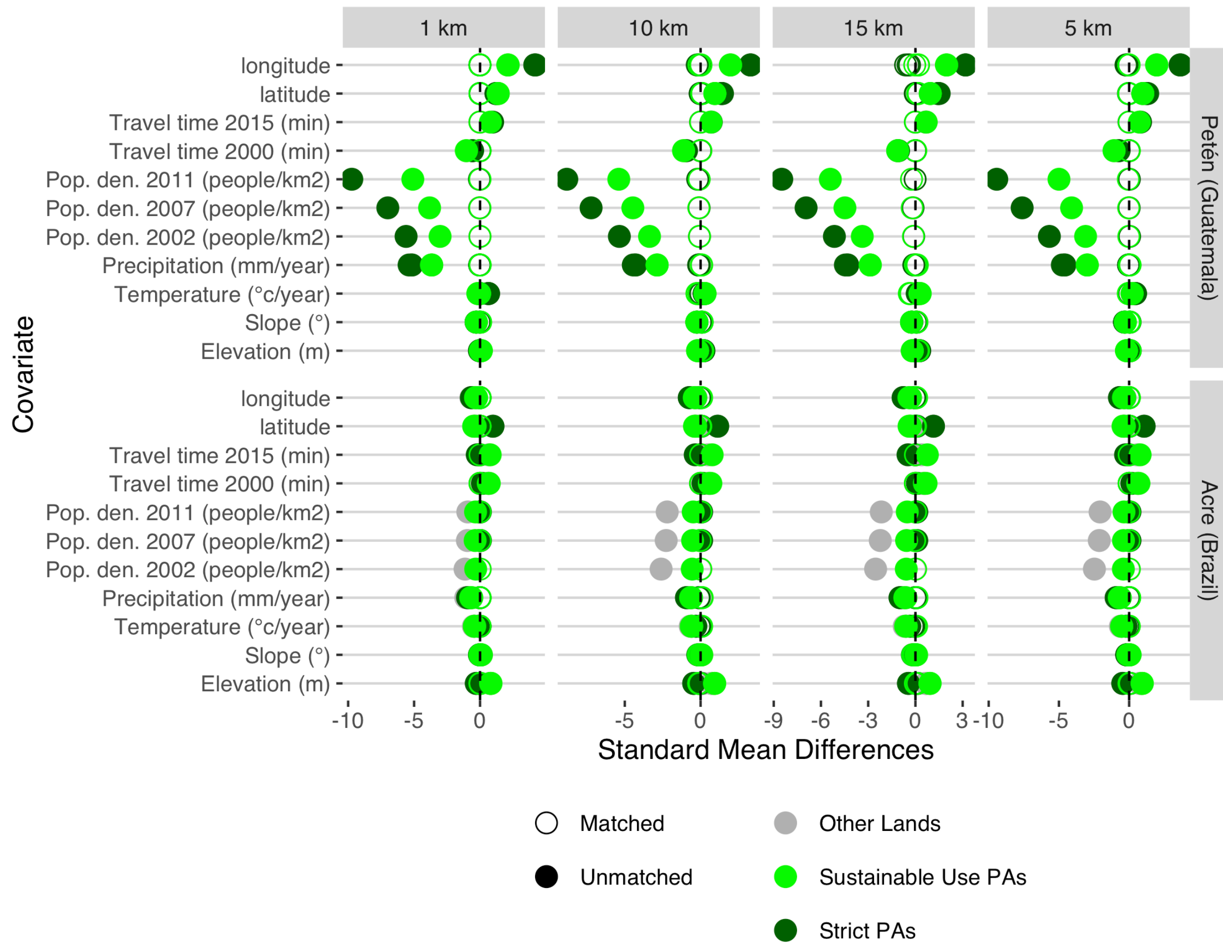


Figure S3. Covariates' standard mean differences between Community Managed PAs and neighboring Other Lands (gray), Sustainable Use PAs (light green), and Strict PAs (dark green) before (Unmatched) and after matching analysis (Matched) in geographic discontinuity designs across Petén (Guatemala) and Acre (Brazil). The covariate standard mean differences are calculated at different distances inside and outside Community Managed PAs boundaries.

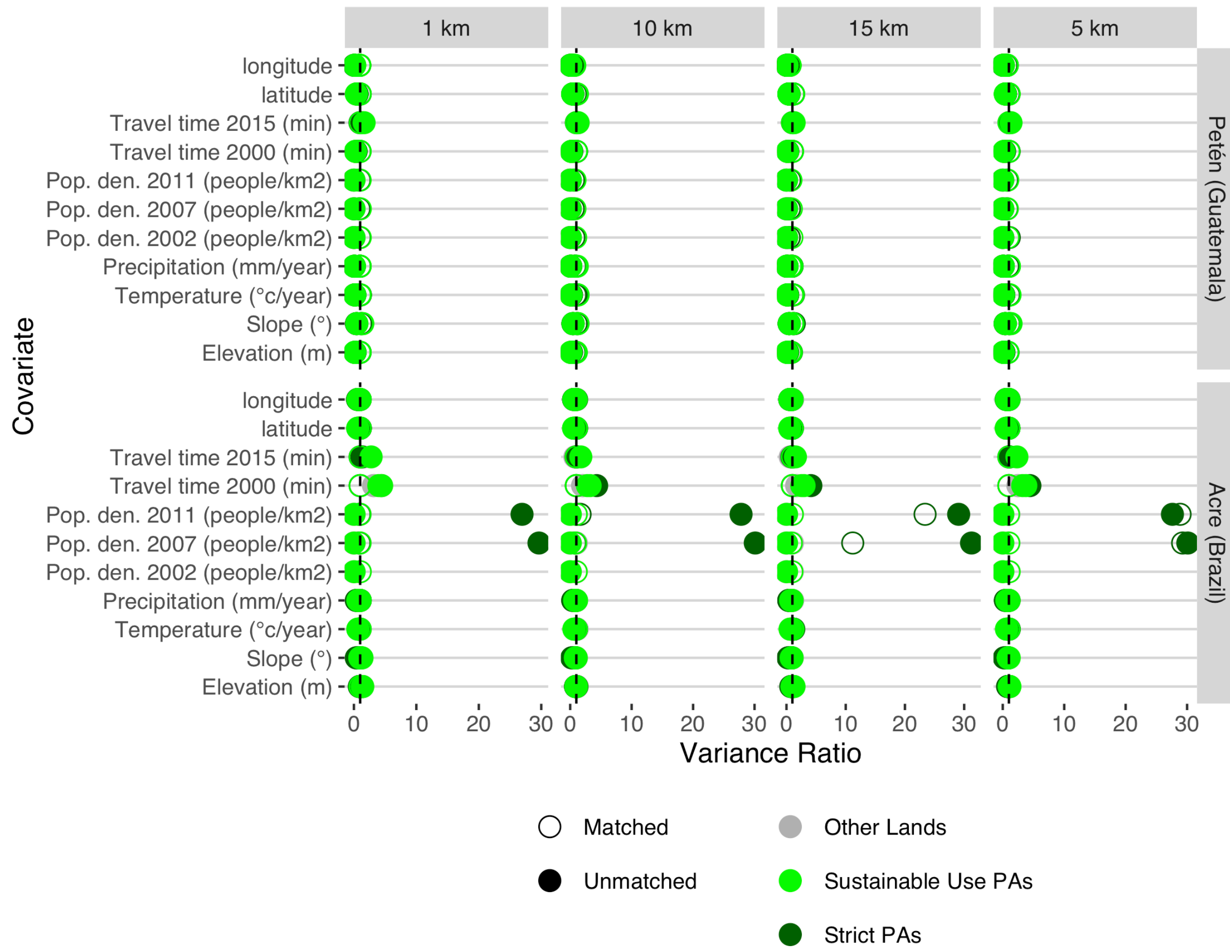


Figure S4. Covariates' variance ratios between Community Managed PAs and Other Lands (gray), Sustainable Use PAs (light green), and Strict PAs (dark green) before (Unmatched) and after matching analysis (Matched) in geographic discontinuity designs across Petén (Guatemala) and Acre (Brazil). The covariate variance ratios are calculated at different distances inside and outside Community Managed PAs boundaries.

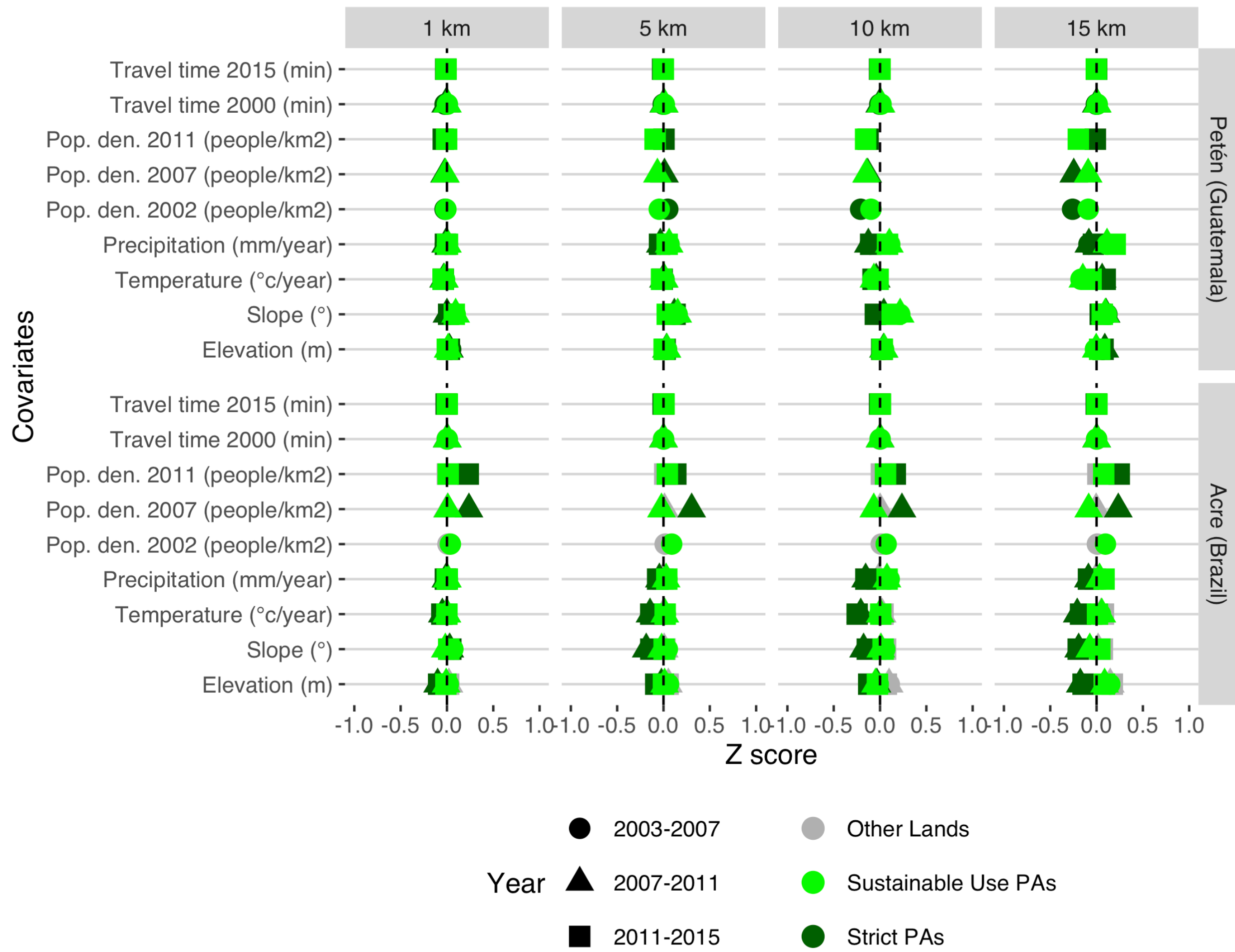


Figure S5. Covariate falsification tests derived from linear mixed models in geographic discontinuity designs across different distances around Community Managed PAs boundaries. The falsification tests the influence of Community Managed PAs on covariates relative to Other Lands (gray), Sustainable Use PAs (light green), and Strict PAs (dark green) after matching analysis and linear mixed models. The Z score represents the number of standard deviations from the mean.

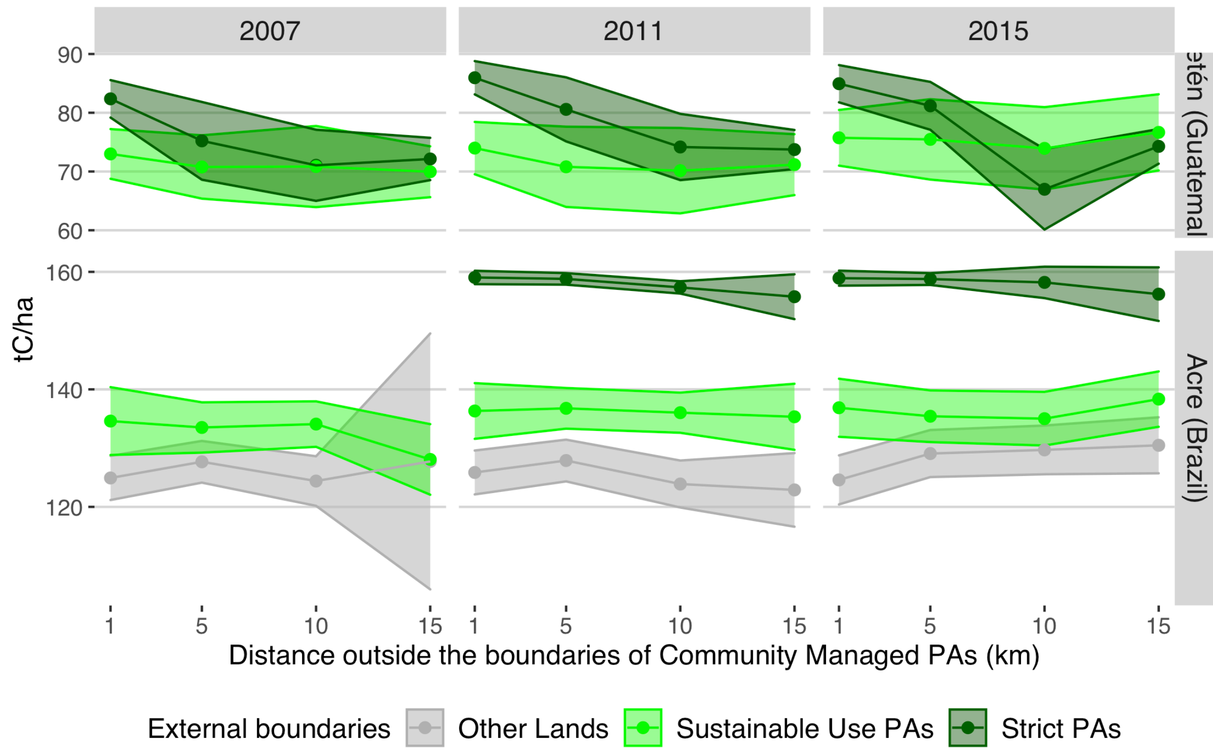


Figure S6. Carbon stocks of land tenures surrounding Community Managed PAs during 2007, 2011, and 2015 in Petén (Guatemala) and Acre (Brazil) after controlling for covariates. The points reflect the amount of carbon stocks outside the boundaries of Community Managed PAs in Other Lands (gray), Sustainable Use PAs (light green), and Strict PAs (dark green).

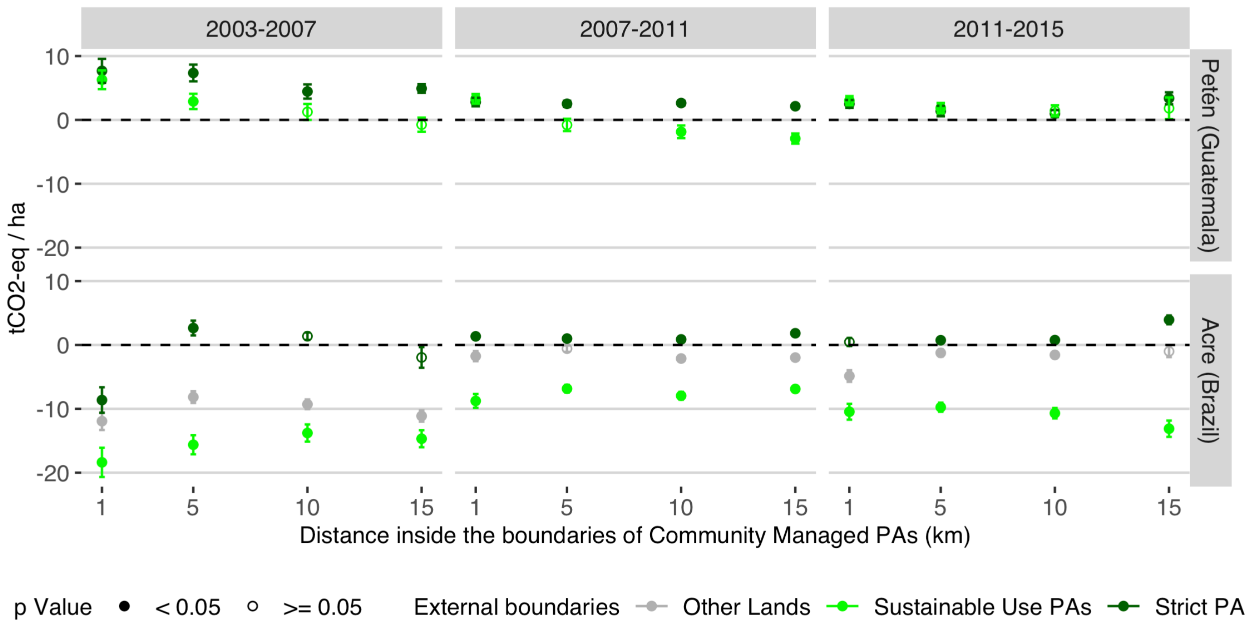


Figure S7. Net carbon changes of land tenures surrounding Community Managed PAs in Petén (Guatemala) and Acre (Brazil) after controlling for covariates. The points reflect the net carbon changes outside the boundaries of Community Managed PAs in Other Lands (gray), Sustainable Use PAs (light green), and Strict PAs (dark green). Negative carbon changes ($p < 0.05$) indicate net carbon emissions relative to Community Managed PAs. Error bars indicate 95% confidence intervals for the net carbon changes.

Chapter 3: Supplementary Material

Supplementary Material 1

	Stable forest	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

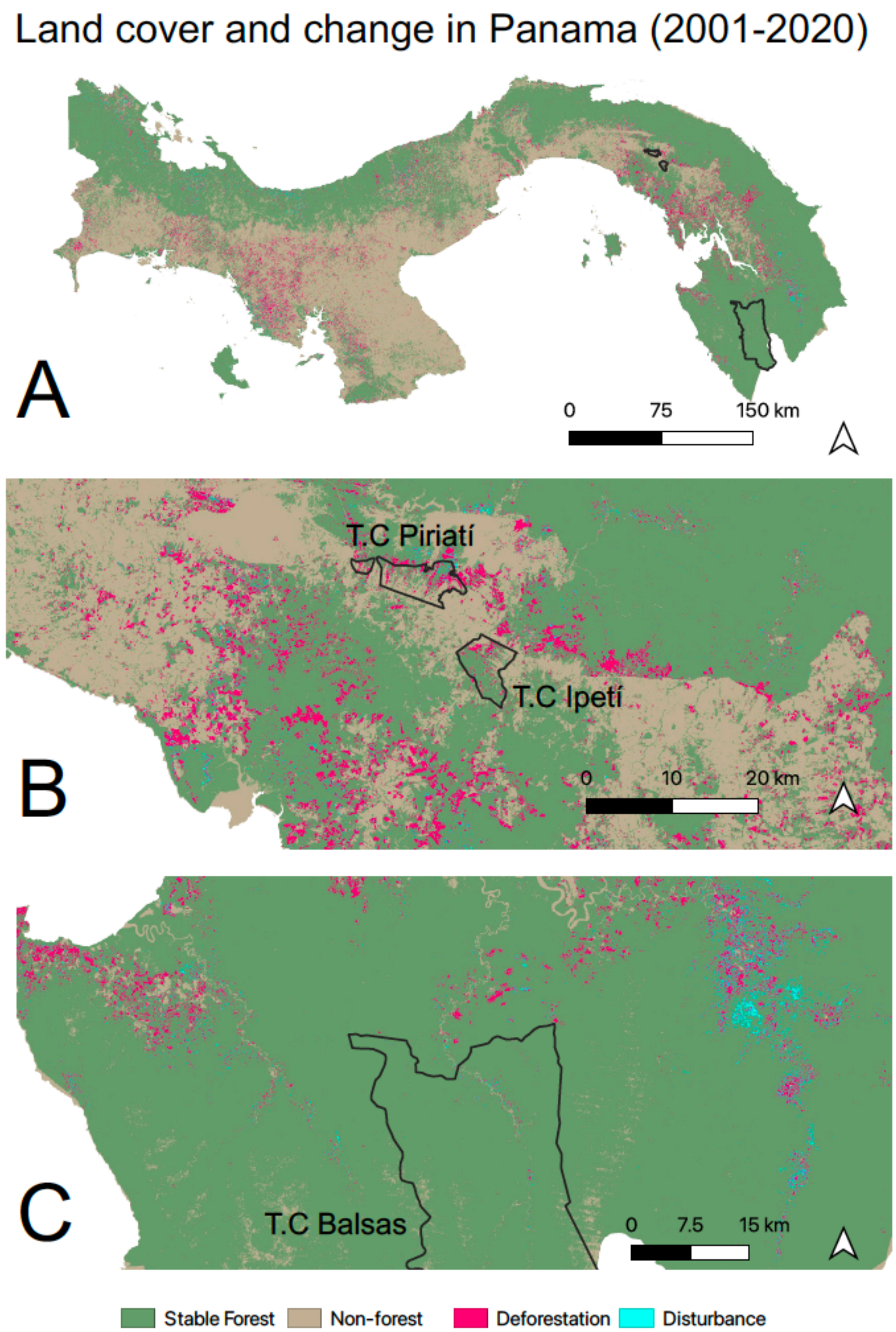
Estimated accuracies from the land-cover change detection obtained through CODED in Google Earth Engine. The user's accuracy expresses the probability that a land cover or land change class detected by CODED will correspond to the reference data (i.e., visual verification on high-resolution satellite imagery and Landsat time series), showing which land cover and land change classes were incorrectly classified. The producer's accuracy expresses the probability that the reference data will correspond to a land cover and land change class detected by CODED, showing which reference data were omitted from the correct land cover or land change class by detected CODED.

Supplementary Material 2

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

General models tested to explain the spatial patterns of deforestation, disturbance, and values regarding nature in Panama's forests. Where $\mathrm{density_i}$ 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. tenure is a factor that indicates if i is in Indigenous Lands or in Other Lands at the national scale. This factor was excluded at the local scale. $\mathrm{b_m}$ and $\mathrm{f(lon_i, lat_i)}$ 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 $\mathrm{f(lon_i, lat_i)}$: spheric splines, Duchon splines, and a gaussian process with exponential correlation (Wood, 2017).

Supplementary Material 3



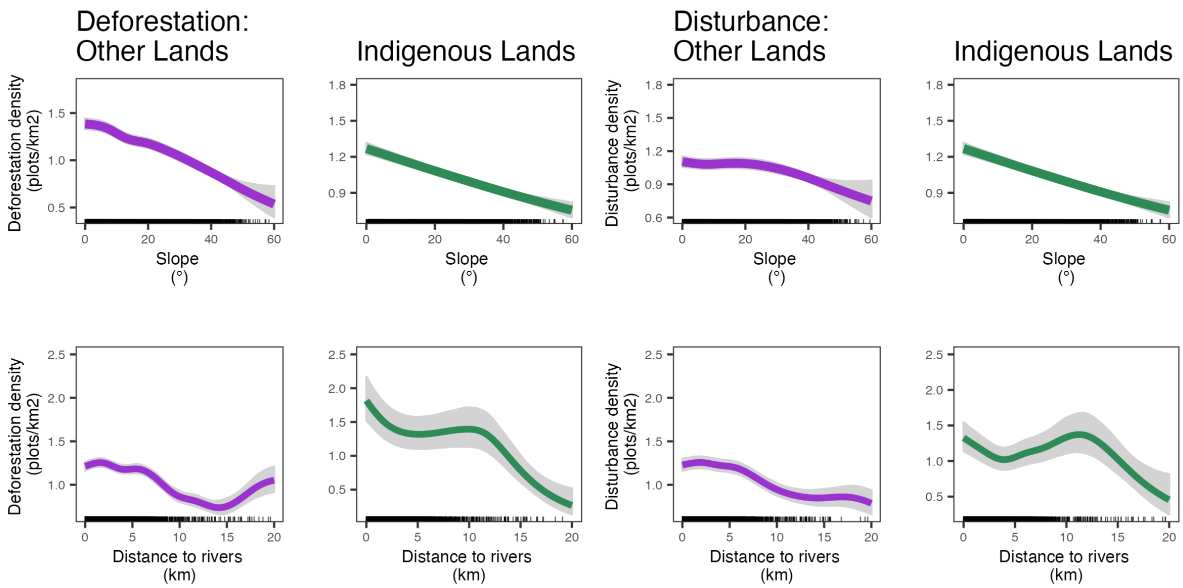
Land cover and change detected by CODED at the national scale (A), the Indigenous Lands (“Tierras Colectivas) of Piriatí and Ipetí and their surroundings in the Bayano region (B), and the northern limits of the Balsas Indigenous Lands and their surroundings in the Darién region.

Supplementary Material 4

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

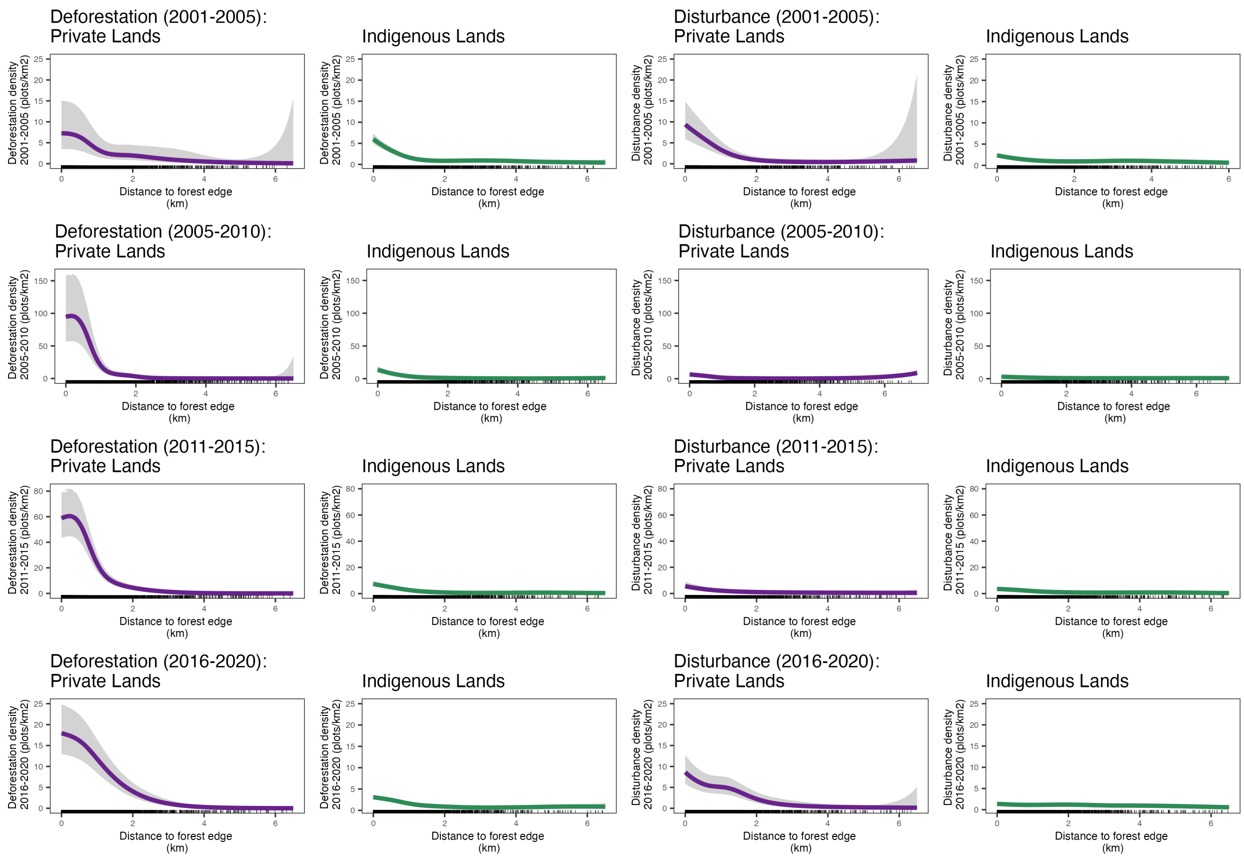
Models tested to infer the spatial patterns of deforestation, disturbance, and values in forests at the national and local scale. The selected models for each scale and outcome variable are highlighted.

Supplementary Material 5



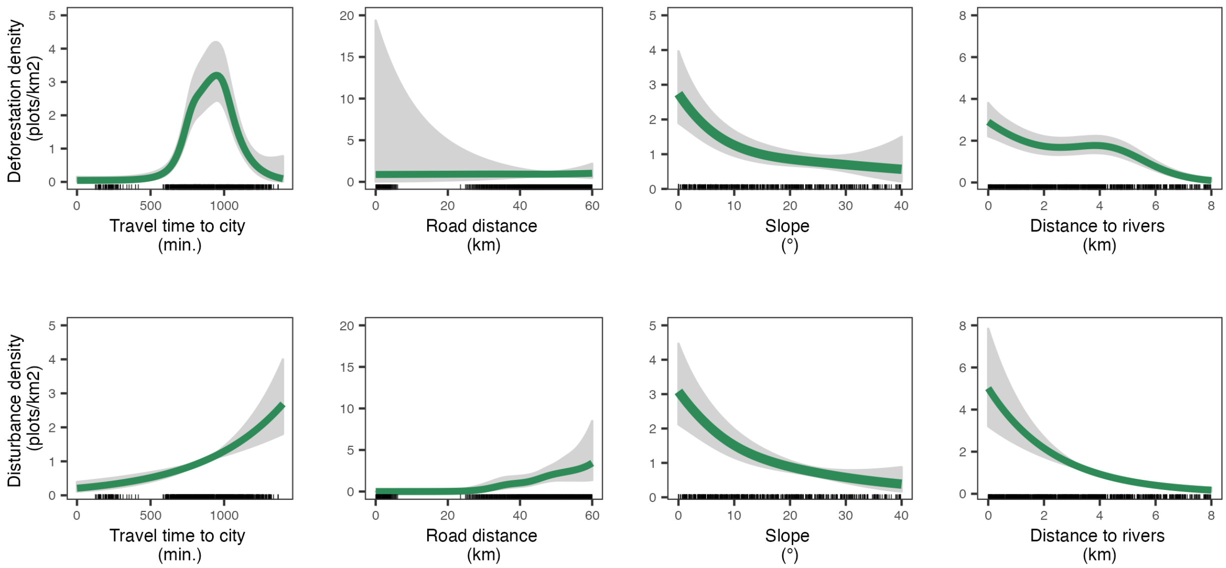
The effects of environmental and socio-economic predictors on deforestation and disturbance density at the national scale during 2001-2020. The national scale compares Indigenous Lands and Other Lands in Panama.

Supplementary Material 6



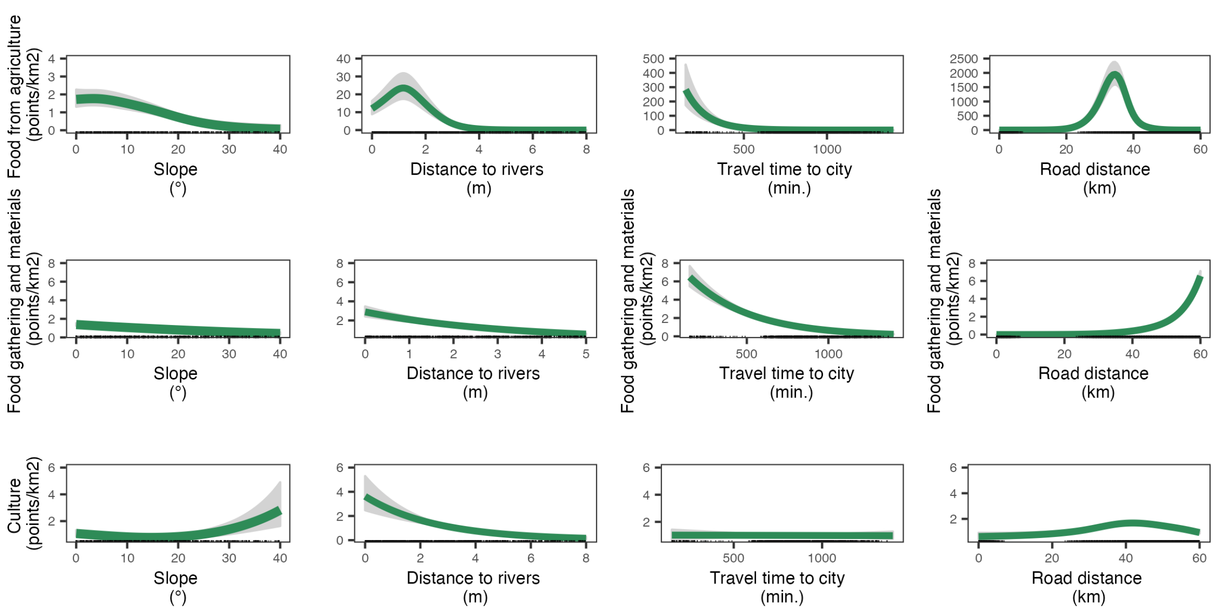
The effects of distance to forest edge on deforestation and disturbance density at the national scale in 4 subperiods between 2001-2020. The national scale compares Indigenous Lands and Other Lands in Panama.

Supplementary Material 7



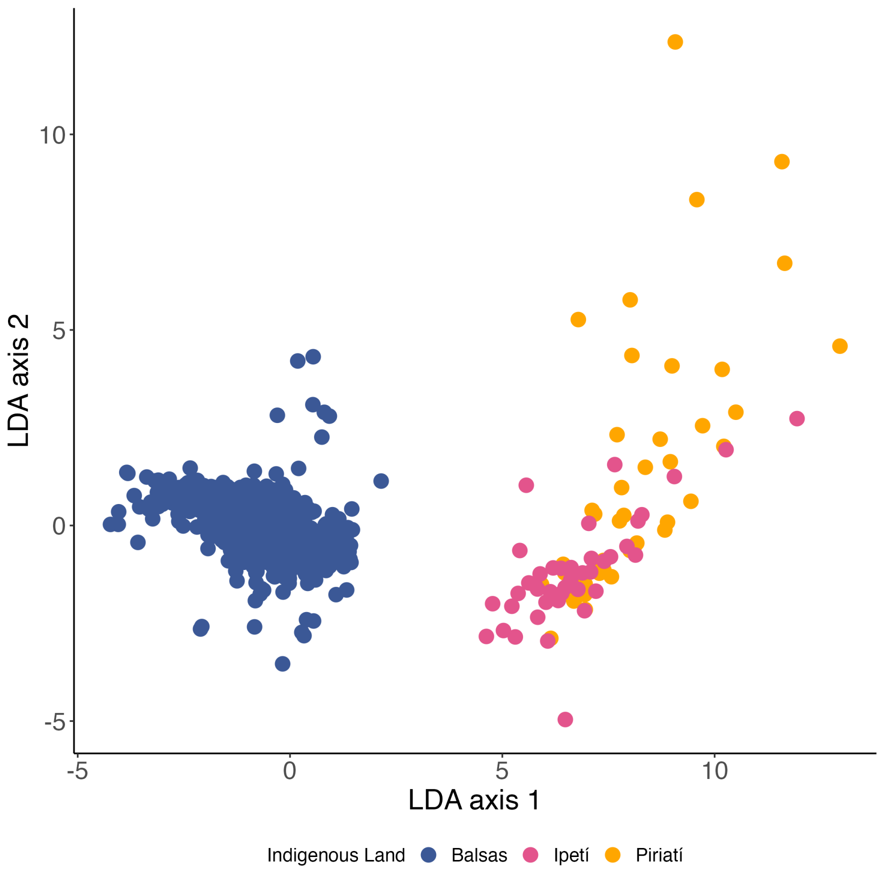
The effects of environmental and socio-economic predictors on deforestation and disturbance density at the local scale during 2001-2020. The local scale corresponds to the Indigenous Lands of Piriatí, Ipetí, and Balsas in eastern Panama.

Supplementary Material 8



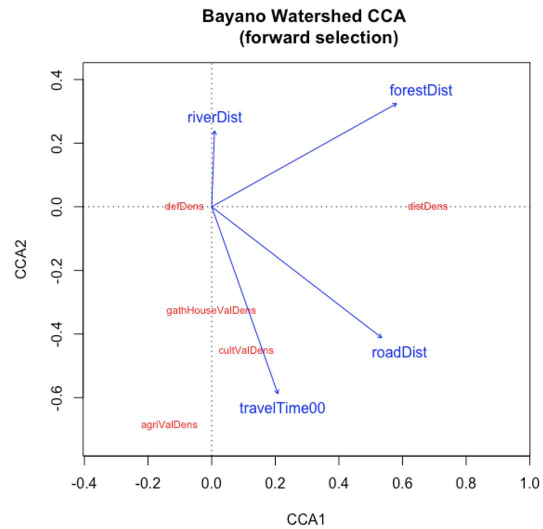
The effects of environmental and socio-economic predictors on values regarding forests at the local scale. The local scale corresponds to the Indigenous Lands of Piriatí, Ipetí, and Balsas in eastern Panama.

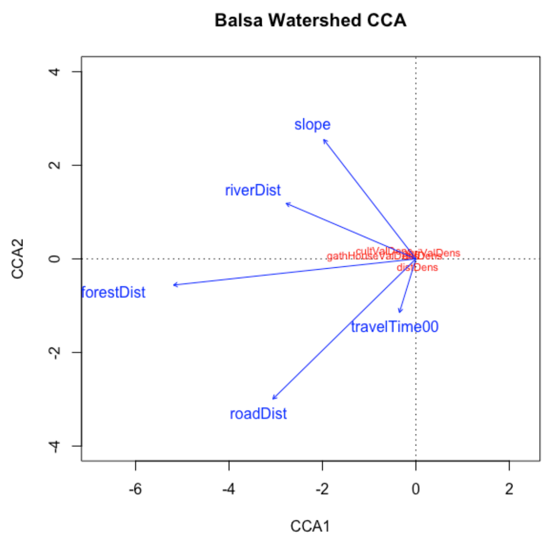
Supplementary Material 9



Linear discriminant analysis (LDA) grouping Indigenous Lands at the local scale based on a matrix of outcome variables and environmental and socio-economic predictors.

Supplementary Material 10





Biplot of canonical correspondence analysis between land cover changes and values in forests (red) (outcome variables) with socio-economic and environmental predictors (blue) (explanatory variables). 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.