Are indigenous territories and community-managed areas effective natural climate solutions? A neotropical analysis using matching methods and geographic discontinuity designs.

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Abstract:

Indigenous Territories (ITs) and Community Managed Protected Areas (PAs) with less restriction on forest use than integral 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 and Community Managed PAs on deforestation, despite the influence of anthropogenic degradation. Thus, little is known about the temporal and spatial effect of allocating ITs and Community Managed PAs on carbon stocks dynamics that account for losses from deforestation and degradation. Using Amazon Basin countries and Panama at the national level, and Petén (Guatemala) and Acre (Brazil) at the subnational level, 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 biases derived from matching analysis and use geographic discontinuity designs to assess the spatial effect of PAs and ITs boundaries on carbon stocks. The temporal effects highlight that allocating ITs preserves carbon stocks and buffer losses as PAs in Panama and Amazon Basin countries. Community Managed PAs temporal effect on carbon stocks surpasses that of integral PAs in Petén (Guatemala) and Acre (Brazil). The geographic discontinuity designs reveal that ITs and Community Managed PAs boundaries secure more extensive carbon stocks than their surroundings, and this difference tends to increase towards the least accessible areas. These results also suggest that indigenous and community land-use in neotropical forests may have a limited and stable spatial impact on carbon stocks. Our findings imply that ITs and Community Managed PAs in neotropical forests support Nationally Determined Contributions (NDCs) under the Paris Agreement. Thus, Indigenous peoples and local communities 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 (1). Protected Areas (PAs), cornerstones of biodiversity conservation, may contribute to these cost-effective solutions by preventing carbon stocks losses (2). However, since 1990, South America and Central America have tripled the area of PAs (3) while simultaneously losing 10% and 25% of forest cover, respectively (4). 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 (5). 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) (6). Other locations with shared governance, such as Community Managed PAs, also seem promising in climate change mitigation (7). Thus, ITs and Community Managed PAs with fewer forest use restrictions and non-centralized governance may conserve forests and potentially represent effective natural climate solutions.

However, the effect of ITs and PAs in forest conservation might be overestimated based on the fact that they tend to be located in higher elevations, steeper slopes, and greater distances to roads and cities than unprotected lands (8,9). To control for this non-random spatial location, an increasing number of studies have relied on a statistical technique called matching analysis (10,11). In these studies, matching analysis samples observations with similar geographical characteristics, removing heterogeneous observations, and allowing to compare protected lands with unprotected areas. For example, using matching analysis, ITs in the Brazilian Amazon have been found to restrain high deforestation pressure more effectively than PAs (12). Panama's PAs and claimed ITs more effectively avoided deforestation than unprotected lands with similar topography and accessibility (13). 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 (2018) concluded that ITs in the Amazon Basin of Colombia, Bolivia and Brazil avoid carbon emissions from deforestation. Similarly, Community Managed PAs, such as community concessions in Petén (Guatemala), and sustainable use areas in Acre (Brazil), have been estimated to avoid deforestation, in contrast to integral PAs that restrict sustainable use, which did not show a discernible effect relative to unprotected lands (16,17). Therefore, controlling for spatial location using matching confirm that ITs and Community Managed PAs are as effective as other 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 protected lands on deforestation. Shifting cultivation, considered a driver of degradation (18), is common among tropical forest landholders (19). After long fallow periods (>20 years), shifting cultivation can only recover around 50% of mature forests' carbon stocks (20). Logging and fires, other causes of degradation in tropical forests, remove 45% and 22% of forest's carbon stocks and take decades to recover (21). Thus, accounting for forest degradation and recovery in temporal carbon stocks dynamics may influence the effectiveness of protected lands in forest conservation, particularly in those with fewer use restrictions (e.g., ITs and Community Managed PAs). However, little is known about the temporal effect of protected lands on carbon stocks dynamics after controlling for spatial location.

Matching analysis controls for the spatial location, but it does not guarantee unambiguous estimates of protected lands' effects in forest conservation. Karsenty et al. (22) 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 protected land (22). In this regard, some have recognized that sampling through matching analysis might not be independent and exclude observations around the boundaries of protected lands (23–25), rather than exploring the implications of sampling across these boundaries. Conversely, the effect of protected lands' boundaries on deforestation has been estimated through regression discontinuity designs. Bonilla-Mejía & Higuera-Mendieta (26) found that ITs' boundaries are more effective than integral PAs at curbing deforestation in Colombia. Similarly, Baragwanath & Bayi (27) 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 (28), and estimate the effect of protected lands' boundaries on carbon stocks. Nor have they addressed whether different forest use levels, such as ITs and PAs, imply different spatial effects on carbon stocks.

This study builds upon previous research assessing the effect of protected lands on deforestation through matching analysis and addresses some limitations of this methodology. Using Panama and Amazon Basin Countries at the national scale, and Petén (Guatemala) and Acre (Brazil) at the subnational scale, this study aims to estimate protected lands' temporal and spatial effects on aboveground carbon stocks. The hypothesis is that protected lands with more restrictions on forest use (e.g., PAs) will secure higher carbon stocks than less restrictive lands (e.g., ITs and Community Managed PAs) over time and throughout their boundaries by reducing the influence of anthropogenic degradation. Regardless of forest use restrictions and governance, we find that protected lands preserve carbon stocks and buffer losses temporarily and spatially across neotropical forests.

Our study makes three contributions to the literature. First, we provide a consistent use of matching analysis in multiple protected lands and countries, allowing us to compare the effects of ITs, OAs, and PAs across Central America and the Amazon Basin. Conversely, previous studies have analyzed either multiple protected lands on a country scale (e.g., 14,17,18) or single protected lands categories across regions (e.g., 11,16). 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 protected lands in climate change mitigation. Furthermore, we explore the spatial biases derived from matching analysis sampling and account for them through geographic discontinuity designs, allowing us to assess the spatial effect of protected lands' boundaries on carbon stocks. To our knowledge, this study is among the first to estimate the effect of multiple protected lands on carbon stocks temporarily (14 years) and spatially (throughout boundaries), providing a quantified estimate of forest conservation and climate change mitigation across Neotropical Forests.

Methods

Geographic scope

This study emerged from 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 (Academic, Research, International and National NGOs) that participate or collaborate with RAISG. Additionally, some of the authors have also previously collaborated with the "Coordinadora de las Organizaciones Indígenas de la Cuenca Amazónica" - COICA (Coordinator of Indigenous Organizations of the Amazon River Basin), and the "Alianza Mesoamericana de Pueblos y Bosques" - AMPB (Mesoamerican Alliance of Peoples and

Forests). These authors' collaborations and the aim to provide indigenous peoples, communities, and countries with a quantified estimate of their forest conservation activities define our study's geographical scope: the Department of Petén (Guatemala), Panama, and the Amazon Basin portions from Colombia, Ecuador, Peru, and Brazil. The study sites cover an area surpassing 10,000 million ha and contain a mosaic of protected lands that include PAs and ITs.

Our study has two scales of analysis: the country-level and the subnational-level. The country-level analysis includes Panama and Amazon Basin Countries (Fig 1). PAs at the country-level encompass national and sub-national 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., claimed lands) were also included at the country-level, except in Colombia, where the data was not available. All ITs overlapping with PAs were defined as OAs. To capture the influence of different governance categories of PAs, we analyzed at the subnational-level two case studies (Fig 2): the Maya Biosphere Reserve in the Department of Petén (Guatemala) and the State of Acre (Brazil). PAs were classified into three governance categories (Table 2): Community Managed PAs, Sustainable Use PAs, and Integral PAs. Community Managed PAs corresponded to Community Concessions from Petén (Guatemala) and Extractive Reserves from Acre (Brazil), where local communities share forests' governance with governments. Sustainable Use PAs are equivalent to IUCN Categories IV, V and VI areas that share governance with governments but do not exclusively involve community management. Finally, Integral PAs corresponded to National Parks with a limited human presence and emphasize on biodiversity conservation equivalent to IUCN I-III. All private and public lands outside ITs, OAs and PAs were defined as other lands in the national and subnational level analyses.

Fig 1. National-level analysis. 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).

	Protected Lands	
National Jurisdiction	Protected Areas (PAs)	Indigenous Territories (ITs)
Panama	National Park Protective Forest Wildlife Refugee Multiple Use Area Forest Reserve Hydrological Reserve Zone of hydrological protection	Titled: "Comarcas" Titled: Collective Territories Claimed/Untitled
Colombia	National Park National Protective Forest Reserve National Forest Reserve Civil Society Nature Reserve Fauna and Flora Sanctuary	Titled: Indigenous Reserve
Ecuador	National Park National Reserve Protective Forests Ecological Conservation Area Biological Reserve Ecological Reserve Fauna Production Reserve Wildlife Refugees	Titled Declared Claimed/Untitled
Peru	National Park National Sanctuary Historical Sanctuary Protective Forest Landscape Reserve Communal Reserve Hunting Reserve Reserved Zone	Titled / Declared: Native community Titled/ Declared: Peasant community Claimed/Untitled

Brazil	National Park	Titled/ Declared: Indigenous Area
	Environmental Protection Area	Titled/ Declared: Native Community
	Area of Relevant Ecological Interest	Titled / Declared: Indigenous Reserve
	Ecological Station	Titled / Declared: Indigenous Territory
	State Forest	Claimed/Untitled
	State Park	
	Wildlife Refugee	
	Biological Reserve	
	Sustainable Use Reserve	
	Extractive Reserve	

Table 1. Protected lands included at the national-level analysis. PAs are equivalent to IUCN categories I-VI. All areas in which ITs overlap with PAs are considered Overlapped Areas (OAs).

Fig 2. Subnational-level analysis. (A) The department of Petén in Guatemala and the state of Acre in the Brazilian Amazon. Protected Areas (PAs) in Petén (Guatemala) (B) and Acre (Brazil) (C). PAs are classified into different governance categories: Community Managed PAs (light green), Sustainable Use PAs (blue-green) and Integral PAs (dark green). Other PAs (white) in Petén correspond to buffer zones and multiple-use areas. Protected Lands (Excluded) (black lines) were not analyzed and correspond to PAs outside the Maya Biosphere Reserve in Petén (Guatemala), and ITs in Acre (Brazil).

Protected Areas (PAs)

Subnational Jurisdiction	Community Managed	Sustainable Use	Integral
Peten (Guatemala)	Community Concessions	Private Concessions and Cooperatives	National Parks Protected Biotopes
Acre (Brazil)	Extractive Reserves	National Forests	National Parks Ecological Stations

Table 2. PAs included at the Subnational-level analysis. PAs classified into different governance categories in Petén (Guatemala) and Acre (Brazil).

Spatial data and processing

The boundaries of protected lands were curated by ACOFOP (Asociación de Comunidades Forestales de Petén) for Petén (Guatemala); 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.

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. (29,30) and Walker et al. (6). 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 national and subnational jurisdictions (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 Petén and Panama (S1 Appendix). 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 protected lands' non-random spatial location by estimating the mean covariate differences between other lands and protected lands in each jurisdiction using Mann Whitney tests (S2 Appendix).

Coarsened exact matching

We performed matching analysis and linear mixed models to control for spatial location and infer the effect of PAs, ITs and OAs (i.e., protected lands) 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 (31). Here, the treatment variable corresponded to land tenure, and matching created subsets of observation units of ~500 m resolution in protected lands and other lands with similar slope, elevation and distance to roads, towns 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) (32) with the R package *MatchIt* (33) for each protected land across the national and subnational levels analyses. Following steps from Iacus et al. (34), we first defined coarsening choices for each covariate (S3 Appendix). For example, the elevation was coarsened in multiple categories based on 100 meters intervals. This coarsening choice meant that protected lands and other lands 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 standardized mean differences between protected lands and other lands below 5% for all covariates (S4 Appendix).

After isolating the effect of spatial location through matching, we made temporal estimates regarding the effect of allocating protected lands on carbon stocks at national and subnational levels. This effect was calculated using linear mixed models in the R package *lme4* (35). Annual carbon density was the outcome variable, and land tenure (protected land or other land) a fixed effect. Additionally, elevation, slope and the distance to roads, towns, and rivers were also defined as fixed effects, spanning any remaining imbalances from the matched subsets. The matched sub-group (matched observation units between protected lands and other lands with similar covariate values) was a random effect to account for the structure of matched subsets. These linear mixed models were estimated annually between 2003 and 2016 in all study sites, for each protected land category separately. Two parameters derived from the linear mixed models were used to determine the effect of protected lands on carbon stocks after controlling for spatial location: the intercept and land tenure. The intercept or the annual carbon density found in other lands represents the carbon stocks baseline for protected lands. The land tenure's effect refers to the annual average differences of carbon stocks between protected lands and other lands after matching, defined as the temporal effect.

Geographic discontinuity designs

After calculating the distance of matched observation units around the boundaries of protected lands, we explored geographic discontinuity designs to estimate the spatial effect of administrative boundaries (36). Specifically, we assessed how protected lands' boundaries influence carbon stocks compared with other neighbouring lands. Our geographic discontinuity designs followed Keele et al. (28), which uses matching methods to find treatment and control observation units with similar covariates, including the geographic distance between observation units. To implement these designs, we created subsets of observation units with buffer zones inside and outside of protected lands boundaries, of 0–1 km, 0–5 km, 0-10 km, and 0–15 km. The boundaries between protected lands (e.g., ITs and PAs) were not tested except in Petén (Guatemala). Some protected lands in the Maya Biosphere Reserve (Petén, Guatemala), such as community concessions (Community Managed PAs) and National Parks (Integral PAs), do not share boundaries with other lands. Therefore, the geographic discontinuity designs in Petén (Guatemala) compared the boundaries of Community Managed PAs with Integral PAs, Sustainable Use PAs, and Other protected lands (i.e., buffer zones and multiples use zones).

After defining the geographic discontinuity designs, we also performed CEM with the buffer zones subsets, including slope, elevation and distance to roads, towns and rivers as covariates. Additionally, we controlled for the geographic distance among observation units according to buffer zones. For example, for buffer zones 0–1 km, we included matches across a 2-km radius, and for 0–15-km buffer zones, a 30-km radius. The differences between average carbon stocks stored inside and outside the boundaries of protected lands, or the spatial effect, was also estimated through the linear mixed models aforementioned. The geographic discontinuity designs estimated the effect of protected lands' boundaries on carbon stocks in 2003 and 2016.

Results

The temporal effect of protected lands on carbon stocks across neotropical countries

Matching analysis controlled the influence of spatial location, allowing to estimate the temporal effect of allocating protected lands on carbon stocks. This temporal effect represents the annual mean difference of carbon stocks between protected lands and other lands (Fig 4). Across Panama and Amazon Basin countries, the carbon stocks from 2003 to 2016 in protected lands were usually higher than other lands (i.e. the baseline), resulting in positive temporal effects. Country-level comparisons of temporal effects reveal three regional patterns. Protected lands in 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's protected lands 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.

Fig 4. The temporal effects of protected lands 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.

The positive temporal effects also reveal the additional amount of carbon stocks secured by allocating protected lands in a particular year across Panama and Amazon Basin countries (Figure 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 IT's and OA's accounted for 35% (19 t C/ha) and 71% (44 t C/ha) additional carbon stocks. Similar to Panama, protected lands 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 5–5.7% (i.e., 5 - 7 t C/ha) in PAs 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, protected lands' temporal effects on carbon stocks remained stable or increased relative to other lands until 2016 (Fig 4, S5 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, protected lands in Panama experienced decreases in temporal effects (> -5%) that seem to be driven by the recovery of carbon stocks in other lands (S6 Appendix). Thus, stable and increasing temporal effects reflect that allocating protected lands buffered losses and secured the stability of carbon stocks relative to the other lands. Furthermore, these results reveal that indigenous lands (ITs and OAs) and PAs secured similar amounts of carbon stocks until 2016.

The subnational-level analysis in Petén (Guatemala) and Acre (Brazil) estimated the temporal effects on carbon stocks of PAs with varied forest governance and restrictions on forest use (Fig 5, S7 Appendix) relative to other lands (S8 Appendix). Community Managed PAs in Petén (Guatemala) (i.e., Community Concessions) had carbon stocks ~60% (28 t C/ha) larger than other lands (95.5 t C/ha) in 2003, and this effect increased to 78% (34 t C/ha) in 2016. Acre's Community Managed PAs (i.e., Extractive reserves) also registered in 2003 larger carbon stocks (6.2%, 8 t C/ha) than other lands (109.4 t C/ha) and an increase in 2016 (9.1%, 11 t C/ha). These temporal effects of Community Managed areas were always greater than Sustainable Use PAs in Petén (Guatemala) and Acre (Brazil). Community Managed PAs at least doubled the temporal effect on carbon stocks of Private Concessions and Cooperatives (Petén, Guatemala), and National Forests (Acre, Brazil). The differences in temporal effects were narrower between Integral PAs and Community Managed PAs. During 2016, Integral PAs exhibited an effect of ~58% (25t C/ha) in Petén (Guatemala) and ~7% (10 t C/ha) in Acre (Brazil). These findings indicate that between 2003 and 2016, Community Managed PAs had a larger effect on carbon stocks than Sustainable Use PAs and integral PAs and highlight the variation among PAs at a subnational scale.

Fig 5. The temporal effects of PAs in Petén (Guatemala) and Acre (Brazil) on carbon stocks 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 Community Managed PAs (light green), Sustainable Use PAs (cyan), and Integral PAs (dark 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.

Insight at a finer scale: The role of protected lands' boundaries 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 protected lands (Fig 6, Table 3). Matched observation units in protected lands 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 the boundaries of protected lands ranged between 3.10 km (± 3.13) (Ecuador) and 9.52 km (± 7.72) (Panama). Not surprisingly, the spatial distributions imply that observations along the boundaries of protected lands are more likely to share spatial features (i.e., elevation, slope, and distance to roads, towns, and rivers). In the case of observations in protected lands, these sampling outcome suggests that matching analysis selects the most accessible areas, omitting the core and possibly more intact forests. Thus, the spatial distribution from matching indicates that the aforementioned temporal effects of protected lands are conservative.

Figure 3. Observation units sampled through matching analysis in protected lands from Panama and Acre. (A). Panama is National-level analysis, including PAs, ITs, and OAs. (B). Acre (Brazil) is a subnational-level analysis and includes different PAs categories.

Jurisdiction	**Land Tenure**	**Mean distance of Matched Observation Units to Protected Lands' 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
Peten (Guatemala)	Other Lands	42.19	29.34
	Strict PAs	3.70	2.89
	Community Managed PAs	2.89	2.35
	Sustainable Use PAs	4.01	2.52
Acre (Brazil)	Other Lands	5.81	10.31
	Strict PAs	4.72	4.92
	Community Managed PAs	2.47	2.99
	Sustainable Use PAs	1.37	1.53

Table 3. Mean distance to protected lands' boundaries of observation units sampled through matching analysis by jurisdiction and land tenure.

Considering the spatial distribution of matched observations, we performed geographic discontinuity designs to understand how carbon stocks varied spatially throughout the boundaries of protected lands in 2003 and 2016. The geographic discontinuity designs estimate spatial effects. That is, the mean differences of carbon stocks inside and outside protected lands for various distances around their boundaries, after controlling for spatial location. Overall, the geographic discontinuity designs show that carbon stocks increase inside the boundaries of protected lands in 2003 and 2016 (Figure 7). As discussed below, the geographic discontinuity designs reveal spatial and spatial-temporal patterns across protected lands.

Figure 7. The spatial effect of protected lands' boundaries 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 a certain buffer distance. Empty points and dashed lines represent the spatial effects in 2003, while full points and continuous lines the spatial effects in 2016. 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 protected lands influence carbon stocks within their boundaries. We found that the spatial effects of protected lands tend to increase with the buffer distance to boundaries, and they are more pronounced in the first 5 km (Figure 7, S9 Appendix). 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 protected lands 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 protected lands bring stability to carbon stocks. We found that from 2003 to 2016, the differences of carbon stocks inside and outside protected lands increased, except for ITs in Colombia (Figure 7). Colombia's ITs secured larger carbon stocks within their boundaries in 2016, but their spatial effect reduced 0.2% at 5km and 10km, potentially driven by a recovery in surrounding areas (S9 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 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 protected lands, especially in OAs.

The geographic discontinuity designs in multiple categories of PAs from Acre (Brazil) and Petén (Guatemala) represent different geographic settings (Figure 8, S10 Appendix). As with country-level results, geographic discontinuities in Acre (Brazil) compared carbon stocks inside and outside PAs' boundaries. At 5km buffers from their boundaries, Community Managed PAs had 8.4% larger carbon stocks than surrounding lands (126 t C/ha) at 5km from their boundaries in 2016. Acre's Sustainable Use PAs and Integral PAs had a more moderate effect, exhibiting a 7.2% and 5.2% increase of carbon stocks inside their boundaries at the same distance and during the same year. Moreover, the spatial effects of Community Managed and Sustainable Use PAs consistently increased with the buffer distance to boundaries, contrasting Integral PAs. The spatial effects in Acre (Brazil) during 2016 exceeded those of 2003, implying the stability of carbon stocks within all PA's boundaries and a decrease outside in other lands (S10 Appendix). Petén (Guatemala) represented another geographic setting where PAs share boundaries inside the Maya Biosphere Reserve. After comparing the boundaries of Community Managed with other PAs categories, at 5 km buffers, we found that these areas stored 3% more carbon than integral PAs, but 0.82% fewer than sustainable use PAs. Compared with 2003, these spatial effects reduced, partially driven by the recovery of PAs surrounding Community Managed PAs (S10 Appendix). Despite the different geographic settings of Acre (Brazil) and Peten (Guatemala), these case studies suggest that the boundaries of Community Managed PAs secure higher carbon stocks than Integral PAs.

Figure 8. The spatial effect of PAs' boundaries on carbon stocks during 2016 in Petén (Guatemala) and Acre (Brazil). Significant temporal effects ($p < 0.05$) are represented as points and percentages, indicating the additional/fewer carbon stocks secured inside the boundaries of Community Managed PAs (light green), Sustainable Use PAs (cyan), and Strict PAs (dark green) relative to surrounding lands at a certain buffer distance. Empty points and dashed lines represent the spatial effects in 2003, while full points and continuous lines the spatial effects in 2016. 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 effect in the Maya Biosphere Reserve (Petén) compares Community Managed PAs with other Protected Lands, Sustainable Use PAs, and Integral PAs. PAs in Acre are compared with Other Lands.

Discussion

In this study, we aim to estimate the temporal and spatial effects of allocating protected lands, namely ITs, PAs and OAs, on carbon stocks across Neotropical Forests from Central America and the Amazon Basin. Considering that these protected lands presumably experience low anthropogenic pressures of forest loss, we control the effect of spatial location. Contrary to our hypothesis, ITs, OAs, and Community Managed PAs generally preserve carbon stocks and buffer losses as much as other PAs with more forest use restrictions. Over time, these protected lands 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 protected lands. These temporal and spatial effects were conservative and had varied patterns across protected lands and jurisdictions.

The effectiveness of protected lands in conserving forests and carbon stocks

Our findings highlight the need for a "spatially explicit" understanding of matching analysis regarding protected lands and forest conservation. Other studies recognize the spatial biases of matching analysis and incorporate more "spatially explicit" methodologies. 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. (2017) in Africa and Zhao et al. (24) 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. (37), 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 protected lands' boundaries (26,27). 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 (10,15,17,38). After exploring the spatial distribution of matched observation units, our findings point that they are biased towards geographic boundaries, causing conservative estimates about protected lands. 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 protected lands' boundaries and maintaining conservative estimates (28). Hence, our study makes a novel methodological contribution to research by integrating matching analysis and geographic discontinuity designs to test the effectiveness of PAs' and ITs' boundaries in conserving carbon stocks across neotropical countries.

By using conservative estimates, our findings support growing evidence indicating that ITs and Community Managed PAs can be as effective as other PAs in forest conservation (6,16,39,40). After controlling for spatial location, 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. (12), who showed that indigenous lands (ITs and OAs) 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 (15) estimates of avoided emissions from deforestation in ITs from Colombia and Brazil (15). 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 (13). These differences with previous studies might be attributable to our outcome variable (annual carbon stocks) that integrates deforestation, degradation, and recovery. Estimating carbon stocks changes offer more accurate estimates regarding the effectiveness of protected lands, especially in countries where degradation emissions equal or exceed those from deforestation (e.g., Colombia, Ecuador, and Peru) (6). Thus, our results demonstrate that indigenous governance or shared governance of forests is as effective as state-based governance in conserving carbon stocks, suggesting that titling ITs and formalizing shared governance in PAs represent a significant impact for avoided land-use emissions in neotropical countries.

Similarly, Community Managed PAs, here, Community Concessions (Petén, Guatemala) and Extractive Reserves (Acre, Brazil), were more effective in conserving carbon stocks than other PAs with sustainable use and strict protection between 2003 and 2016. Regarding the effectiveness of Community Concessions over Integral PAs, our results are consistent with Blackman's (16) estimates of avoided deforestation. Additionally, we established that Community Concessions are more effective than Private Concessions and Cooperatives in preserving carbon stocks between 2003 and 2016. Other studies also established that PAs with sustainable use in Acre (Brazil) significantly reduce deforestation (17). According to our results, the greatest impact in avoiding the loss of carbon stocks is found in Extractive Reserves, while the impact of National Forests was marginal. Hence, our results indicate that Community Managed PAs, as ITs and OAs, actively avoid the loss of carbon stocks and bring stability to forests. Moreover, our results imply that allocating Community Managed PAs, ITs, and OAs, while providing material and cultural benefits to their inhabitants, can have a pivotal role in climate change mitigation as other PAs.

Our geographic discontinuity designs provide conservative estimates regarding protected land's effect on carbon stocks within their boundaries. Although the assessments of PA's boundaries is common in the literature (41), they do not control for spatial location or compare different categories protected lands. Overall, our findings indicate that carbon stocks increase inside the boundaries of protected lands. However, the spatial effects are variable among PAs. For example, PAs from Colombia seem only to avoid carbon stock losses more than 5 km inside their boundaries in 2003 and 2016. These spatial patterns are not due to recent anthropogenic pressures and confirm the inability of PAs' to reduce forest loss inside their boundaries (26,42,43). Conversely, our results show that ITs, OAs, and Community Managed PAs 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 (27) and titled IT's in Colombia (26) which gradually decrease deforestation inside their boundaries. These gradual reductions in deforestation and degradation imply that indigenous and community land use, presumably for local livelihoods, reduce carbon stocks in the most accessible forests while conserving core areas. Other studies have shown on a local scale the limited impacts of indigenous land use, such as shifting agriculture and agroforestry, on carbon stocks (44,45). Additionally, our results reveal that these spatial effect of protected lands remains temporarily stable. Case studies from Mexico and Ecuador suggest that land-use is temporarily stable in ITs (46,47). Our results, after controlling for spatial location, are among the first to establish that indigenous and community 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 protected lands on carbon stocks is influenced by national contexts. Overall geographical trends indicate that protected lands 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 (48) and the Brazil (49). Moreover, the increasing differences in carbon stocks among protected lands and other lands that we found even after controlling for spatial location, highlight a growing pressure on neotropical forests. Consequuently, the capacity of protected lands to preserve or reduce carbon stock losses is likely to change. Between 2000 and 2013, tropical South America and Guatemala lost 7.3% and 13% of intact forest lands, respectively, mostly caused by the expansion of agriculture (50). Community Concessions in Petén (Guatemala) are challenged by changing concession statuses and land invasions (7). PAs in Colombia are witnessing an increase in deforestation around their boundaries after the Peace Agreement with the Revolutionary Armed Forces (FARC) (43). ITs and PAs in southern Peru are threatened by growing road infrastructure, land invasions, illegal gold mining, and coca production (51). Oil blocks in the Ecuadorian Amazon will expand in cover from 32% to 68%, overlapping with biodiversity hotspots in PAs and ITs (52). 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 (53). Land invasions and deforestation in Panama also pose a threat to ITs (54). In this sense, as deforestation and degradation persist, countries' climate benefits from forests are increasingly dependent on the stability of ITs 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 level (55,56).

Finally, our study has some limitations. Regarding covariates of spatial location, the data included in our analysis do not capture the influence of rapidly changing roads. Nevertheless, the covariates included in this study still create a general classification of accessibility and forest loss pressures to control for the non-random location of protected lands. Despite using a stratified sampling matching, known to effectively reduce covariate imbalances and the variability of treatment effects (e.g., temporal and spatial effects) (57), further research would benefit from comparing stratified and random sampling matching. We also aimed to identify the overall influence of protected land categories, but they may represent different 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 (58), which is not necessarily the case in other countries. Even in our sub-national case study in Petén (Guatemala), Community Concessions represent a diverse mosaic of community-based organizations with particular land-use dynamics (16,59). 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 the effectiveness of protected lands beyond deforestation.

Conclusions

After controlling the influence of spatial location, we found that protected lands with fewer restrictions on forest use represent effective natural climate solutions. Particularly, indigenous lands (ITs, OAs) and PAs have similar temporal and spatial effects on carbon stocks in Panama and Amazon Basin countries. A similar effect also emerges when comparing Community Concessions in Petén (Guatemala) and Extractive Reserves in Acre (Brazil) with Integral PAs. Considering that the observation units sampled by matching are located along the boundaries of protected lands, these temporal and spatial effects are conservative. Consequently, our findings show that indigenous peoples and local communities 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 (60). For the critical role they play in reducing net carbon emissions, indigenous peoples and local communities must become recipients of such benefits, independent of the opportunity costs of avoided deforestation and degradation (61).

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Supplementary Material

Jurisdiction	Geo-spatial Information	Source
All regions	Annual carbon density (2003 – 2016)	Woods Hole Research Center (Baccini et al., 2012; Baccini et al., 2017).
All regions	Elevation and sope	Shuttle Radar Topographic Mission – USGS (United States Geological Survey)
Petén (Guatemala)	Roads, Towns (> 5000 inhabitants), Rivers.	IDEG ("Infraestructura de datos espaciales de Guatemala").
Petén (Guatemala)	PAs, Forest Concessions, and Multiple Use Zones.	ACOFOP ("Asociación de Comunidades Forestales de Petén"), Alianza Mesoamericana de los Pueblos, Prisma.
Panama	Roads, Towns (> 5000 inhabitants), Rivers, PAs.	STRI (“Smithsonian Tropical Research Institute”).
Panama	Titled and Claimed ITs	Neotropical Ecology Laboratory (Prof. Catherin Potvin Universidad de McGill/STRI), COONAPIP (Coordinadora Nacional de los Pueblos Indígenas de Panamá).
Amazon Basin (Colombia,	PAs and ITs, Roads	RAISG (Red Amazónica de Información Socio-Ambiental Geo-Referenciada).

Ecuador, Perú, Brasil).		
Colombia	Rivers	IGAC ("Instituto Geográfico Agustín Codazzi").
Colombia	Settlements (> 5000 inhabitants)	DANE (Departamento Administrativo Nacional de Estadística).
Ecuador	Settlements (> 10 000 inhabitants), Rivers.	IGM ("Instituto Geográfico Militar”).
Peru	Rivers	IGN ("Instituto Geográfico Nacional").
Peru	Settlements (> 5000 inhabitants)	INEI (“Instituto Nacional de Estadística e Informática”) and Ministry of Education.
Brazil	Settlements (> 5000 inhabitants), Rivers.	IBGE ("Instituto Brasileiro de Geografía e estadística”).

S1 Appendix. Geospatial Information and its sources by jurisdiction.

Jurisdiction	Protected Lands	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***
Brazil	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***
Petén (Guatemala)	Integral PAs	-2.65***	-9.14***	-3.12***	70.00***	0.00***
	Community Managed PAs	2.01***	-6.18***	-2.72***	23.00***	0.00***
	Sustainable Use PAs	-1.38***	-5.33***	-1.26***	65.00***	0.00***
Acre (Brazil)	Integral PAs	19.24***	-284***	-29.30***	-47.80***	-0.01***
	Community Managed PAs	24.56***	5.11***	18.08***	29.99***	0.02***
	Sustainable Use PAs	43.79***	-25.50***	17.15***	24.45***	0.06***

S2 Appendix. Covariates mean differences between other lands and protected lands by jurisdiction and their statistical significance from Mann Whitney U tests. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

		Covariates				
Jurisdiction	**Protected Land**	**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
Petén (Guatemala)	Integral PAs	1	1	1	100	1
	Community Managed PAs	1	1	1	100	1
	Sustainable Use PAs	1	1	1	100	1
Acre (Brazil)	Integral PAs	1	1	1	100	1
	Community Managed PAs	1	1	1	200	1.5
	Sustainable Use PAs	1	1	1	200	1.5

S3 Appendix. Coarsening Choices applied through Coarsened Exact Matching (CEM) by jurisdiction across protected lands (PAs, ITs, and OAs).

S4 Appendix. Standard mean differences of covariates among other lands and protected lands before (Pre-Match) (full circles) and after matching analysis (Matched) (empty circles) across national-level and subnational-level jurisdictions. At the National-level (Panama, Colombia, Ecuador, Peru, and Brazil) protected lands are classified as ITs (orange), OAs (yellow), and PAs (green). At the subnational-level (Petén and Acre), protected lands correspond to Community-Managed PAs (light green), Sustainable Use PAs (cyan), and Integral PAs (dark green). The standard mean difference expresses the size of the covariate imbalance between other lands and a particular protected land relative to their pooled standard deviation. Negative values imply higher covariate values in protected lands than other lands.

S5 Appendix. The temporal effect of ITs (orange), OAs (yellow), and PAs (green) on aboveground carbon stocks across neotropical countries. Each point represents the significant annual effects ($p < 0.05$) of protected lands (ITs, OAs, and PAs). The temporal effects are the annual differences of carbon stocks in protected lands and 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.

S6 Appendix. **The carbon stocks baseline of ITs (orange), OAs (yellow), and PAs (green) across neotropical countries.** Each point represents the mean annual carbon stocks found in other lands (i.e., carbon stocks baseline) that share a spatial location similar to protected lands (ITs, OAs, PAs) after matching analysis and linear mixed models. Error bars reflect 95% confidence intervals for the carbon stocks baselines derived from the linear mixed models.

S7 Appendix. The temporal effect of Protected Areas (PAs) in Petén (Guatemala) and Acre (Brazil) on carbon stocks. The Community Managed PAs (light green) correspond to Community Concessions in the Maya Biosphere Reserve in Petén (Guatemala) and Extractive Reserves in Acre, Brazil (IUCN VI). Sustainable Use PAs (cyan) correspond to Private Concessions and Cooperatives in the Maya Biosphere Reserve (Petén, Guatemala) and National and State Forests in Acre (Brazil). Integral PAs (dark green) comprise IUCN categories I-IV in each jurisdiction. Each point represents the significant temporal effects of PAs. These temporal effects are the annual differences of carbon stocks in PAs and other lands after controlling for the spatial location through matching analysis and linear mixed models. Error bars reflect 95% confidence intervals for the temporal effects derived from the linear mixed models.

S8 Appendix. The carbon stocks baseline of PAs categories in Petén (Guatemala) and Acre (Brazil) on carbon stocks. The Community Managed PAs (light green) correspond to Community Concessions in the Maya Biosphere Reserve in Petén (Guatemala) and Extractive Reserves in Acre, Brazil (IUCN VI). Sustainable Use PAs (cyan) correspond to Private

Concessions and Cooperatives in the Maya Biosphere Reserve (Petén, Guatemala) and National and State Forests in Acre (Brazil). Integral PAs (dark green) comprise IUCN categories I-IV in each jurisdiction. Each point represents the mean annual carbon stocks found in other lands (i.e., carbon stocks baseline) that share a spatial location similar to PAs categories after matching analysis and linear mixed models. Error bars reflect 95% confidence intervals for the carbon stocks baselines derived from the linear mixed models.

S9 Appendix. The carbon stocks baseline outside the boundaries of 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 distance,. Error bars reflect 95% confidence intervals for the carbon stocks baselines derived from the linear mixed models.

S10 Appendix. The carbon stocks baseline outside PAs' boundaries in Petén (Guatemala) and Acre (Brazil). The Community Managed PAs (light green) correspond to Community Concessions in the Maya Biosphere Reserve in Petén (Guatemala), and Extractive Reserves in Acre, Brazil (IUCN VI). Sustainable Use PAs (cyan) correspond to Private Concessions and Cooperatives in the Maya Biosphere Reserve (Petén, Guatemala) and National and State Forests in Acre (Brazil). Integral PAs (dark green) comprise IUCN categories I-IV in each jurisdiction. Each dot represents the mean annual carbon stocks found in other lands (i.e., carbon stocks baseline) outside PAs' boundaries at a certain distance, according to geographic discontinuity designs. Error bars reflect 95% confidence intervals for the carbon stocks baselines derived from the linear mixed models.

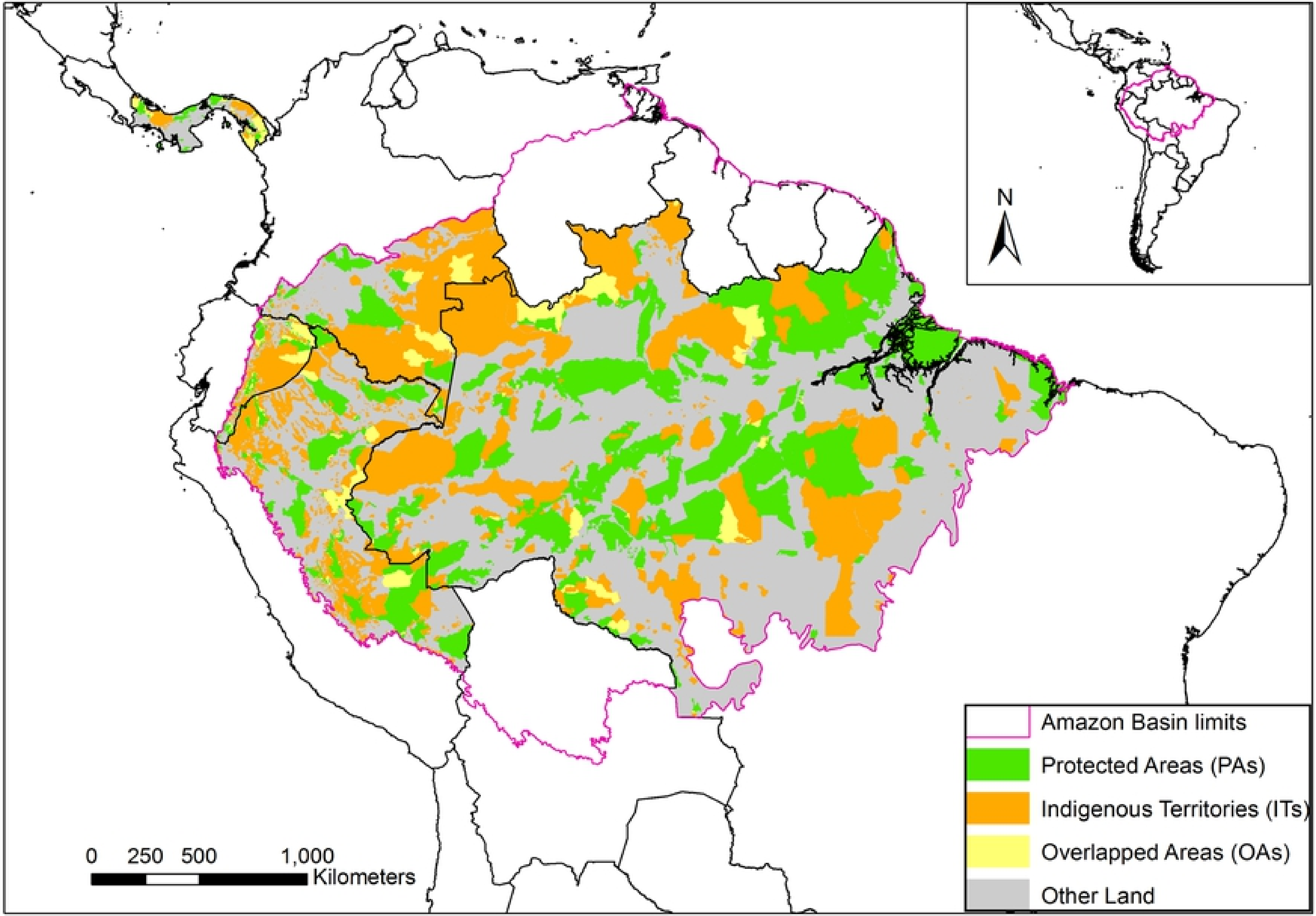
N
Amazon Basin limits
Protected Areas (PAs)
Indigenous Territories (ITs)
Overlapped Areas (OAs)
Other Land
0 250 500 1,000
Kilometers

Fig 1

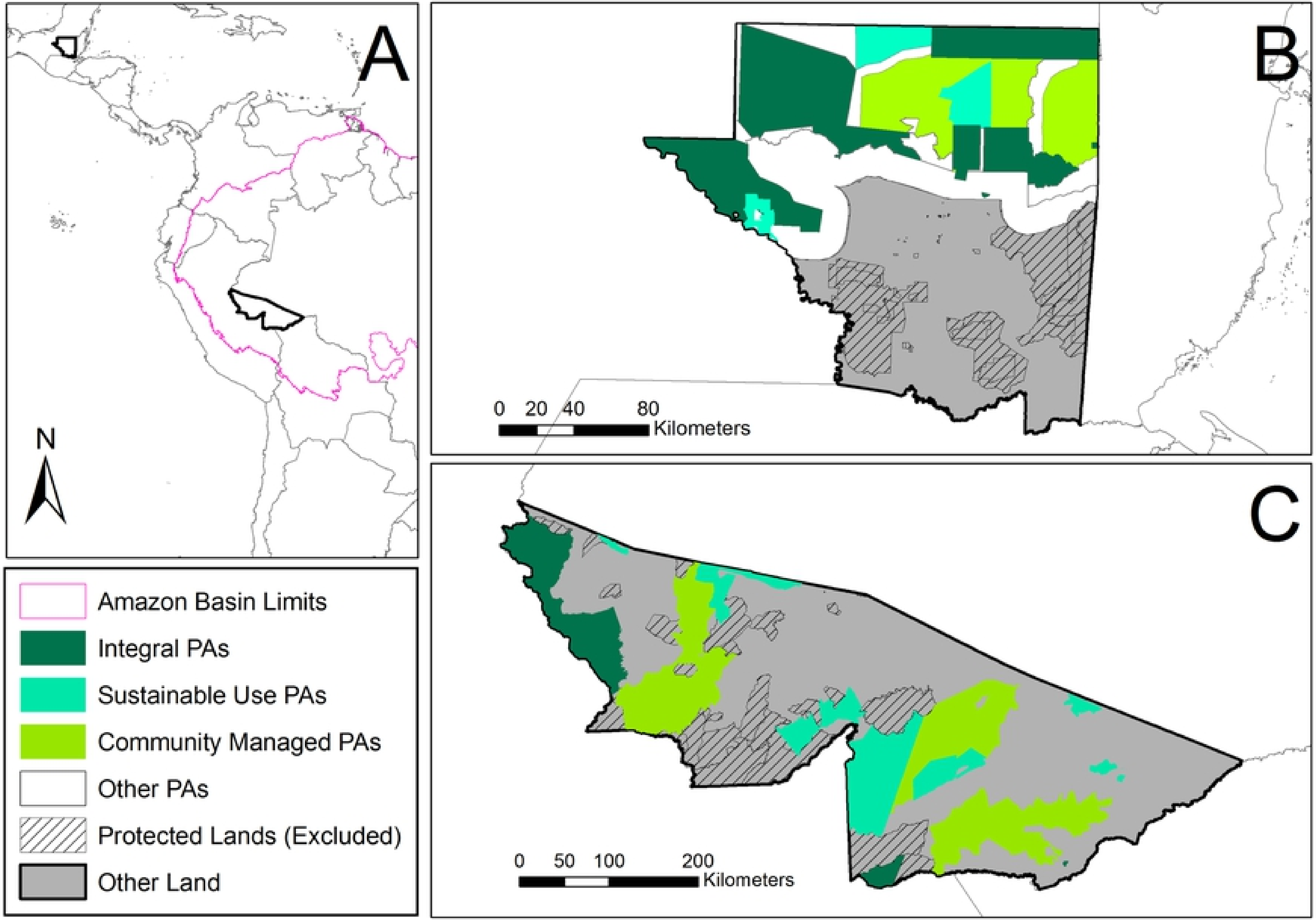
A
N
B
0 20 40 80
Kilometers
C
0 50 100 200
Kilometers
Amazon Basin Limits
Integral PAs
Sustainable Use PAs
Community Managed PAs
Other PAs
Protected Lands (Excluded)
Other Land

Fig 2

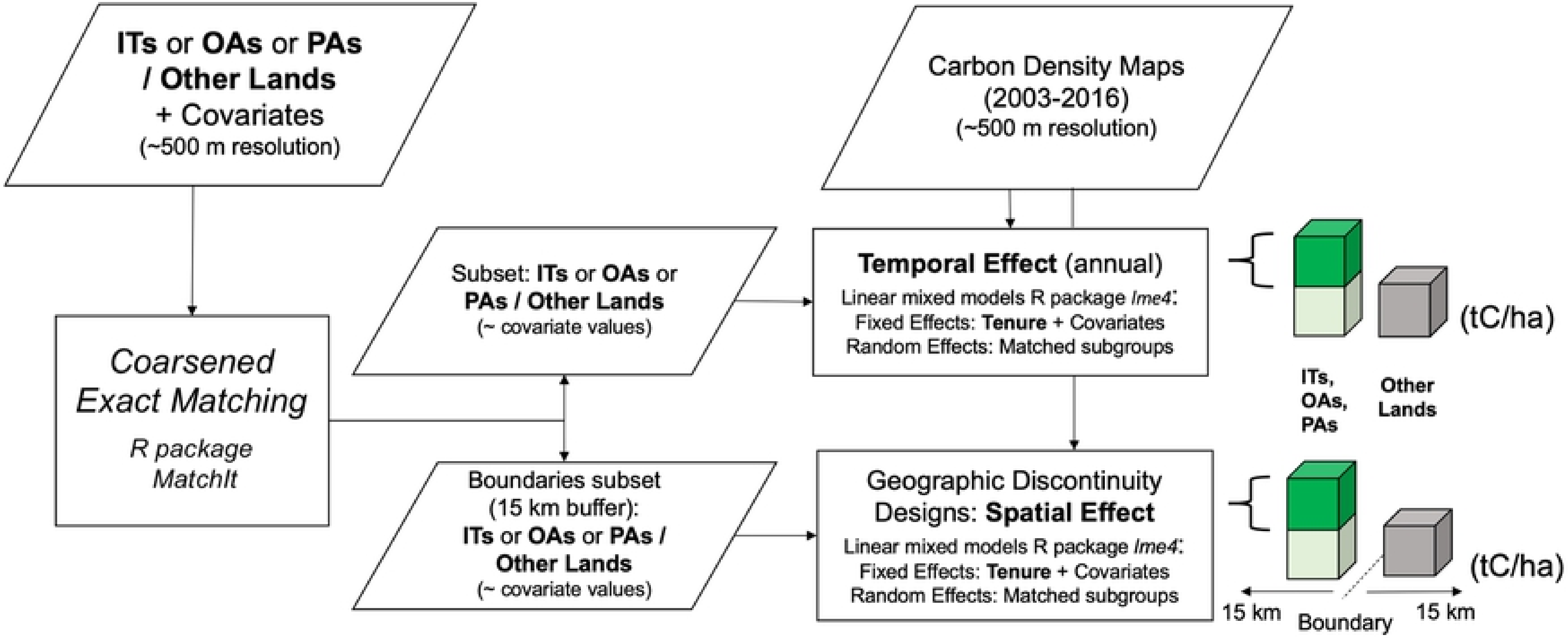
ITs or **OAs** or **PAs**
/ Other Lands
+ Covariates
(~500 m resolution)
Carbon Density Maps
(2003-2016)
(~500 m resolution)
Coarsened Exact Matching
R package MatchIt
Subset: **ITs** or **OAs** or **PAs / Other Lands**
(~ covariate values)
Boundaries subset (15 km buffer):
ITs or **OAs** or **PAs / Other Lands**
(~ covariate values)
Temporal Effect (annual)
Linear mixed models R package *lme4*:
Fixed Effects: **Tenure** + Covariates
Random Effects: Matched subgroups
Geographic Discontinuity Designs: **Spatial Effect**
Linear mixed models R package *lme4*:
Fixed Effects: **Tenure** + Covariates
Random Effects: Matched subgroups
(tC/ha)
ITs, OAs, PAs
Other Lands
(tC/ha)
15 km
Boundary
15 km

Fig 3

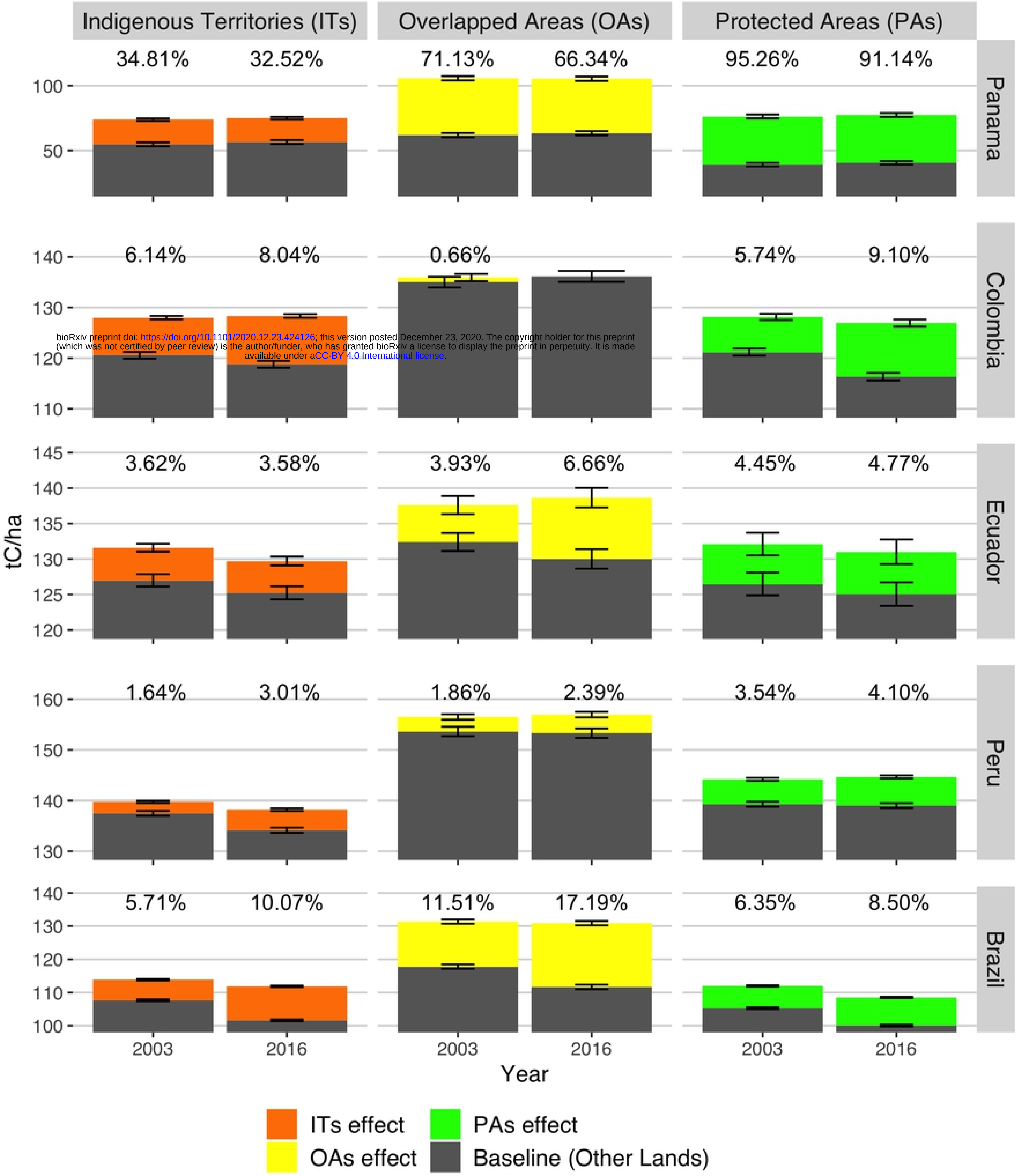
Indigenous Territories (ITs)
Overlapped Areas (OAs)
Protected Areas (PAs)
Panama
34.81%
32.52%
71.13%
66.34%
95.26%
91.14%
100
50
Colombia
6.14%
8.04%
0.66%
5.74%
9.10%
140
130
120
110
Ecuador
3.62%
3.58%
3.93%
6.66%
4.45%
4.77%
145
140
135
130
125
120
Peru
1.64%
3.01%
1.86%
2.39%
3.54%
4.10%
160
150
140
130
Brazil
5.71%
10.07%
11.51%
17.19%
6.35%
8.50%
140
130
120
110
100
tC/ha
2003
2016
Year
🟧 ITs effect
🟩 PAs effect
🟨 OAs effect
⬛ Baseline (Other Lands)

Fig 4

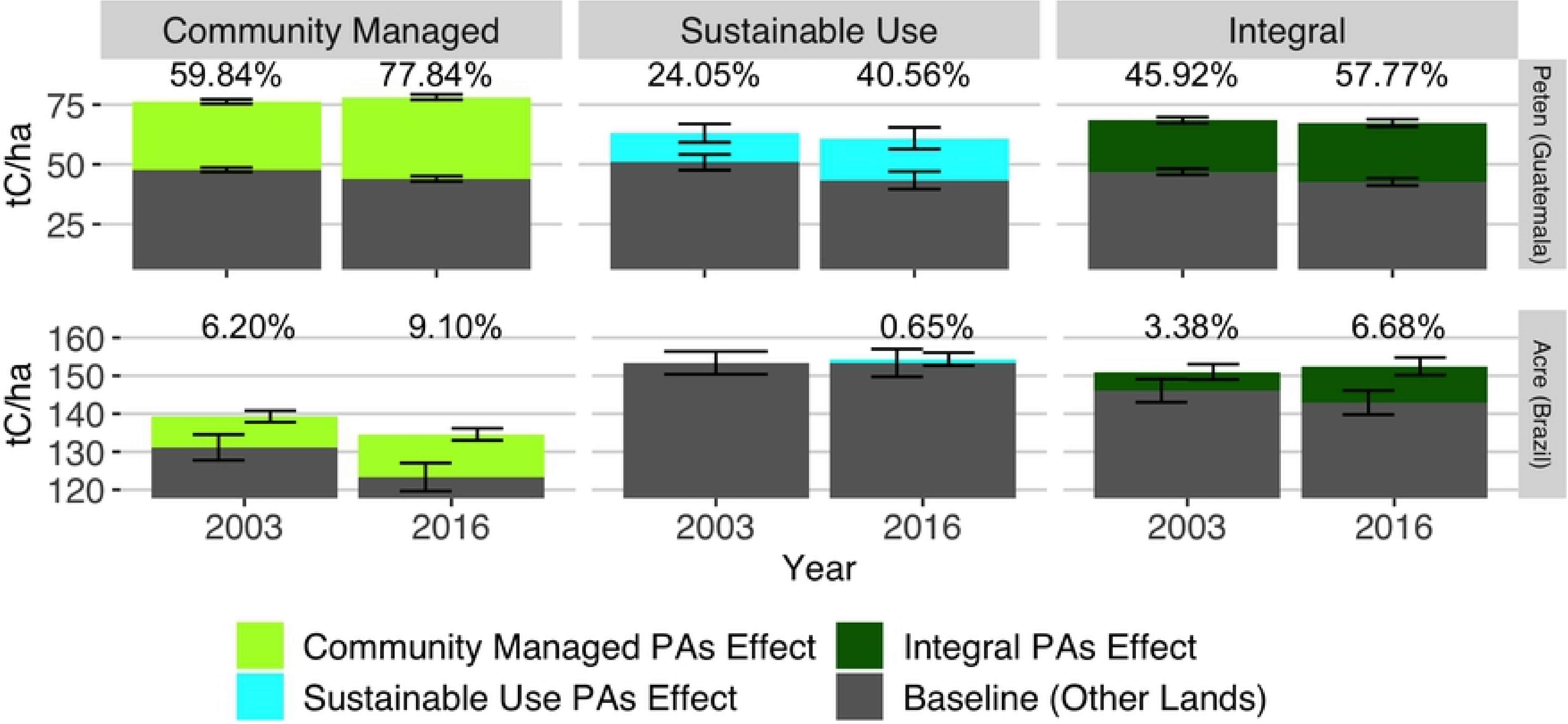
Community Managed
Sustainable Use
Integral
59.84%
77.84%
24.05%
40.56%
45.92%
57.77%
Peten (Guatemala)
tC/ha
75
50
25
6.20%
9.10%
0.65%
3.38%
6.68%
Acre (Brazil)
tC/ha
160
150
140
130
120
2003
2016
2003
2016
2003
2016
Year
Community Managed PAs Effect
Sustainable Use PAs Effect
Integral PAs Effect
Baseline (Other Lands)

Fig 5

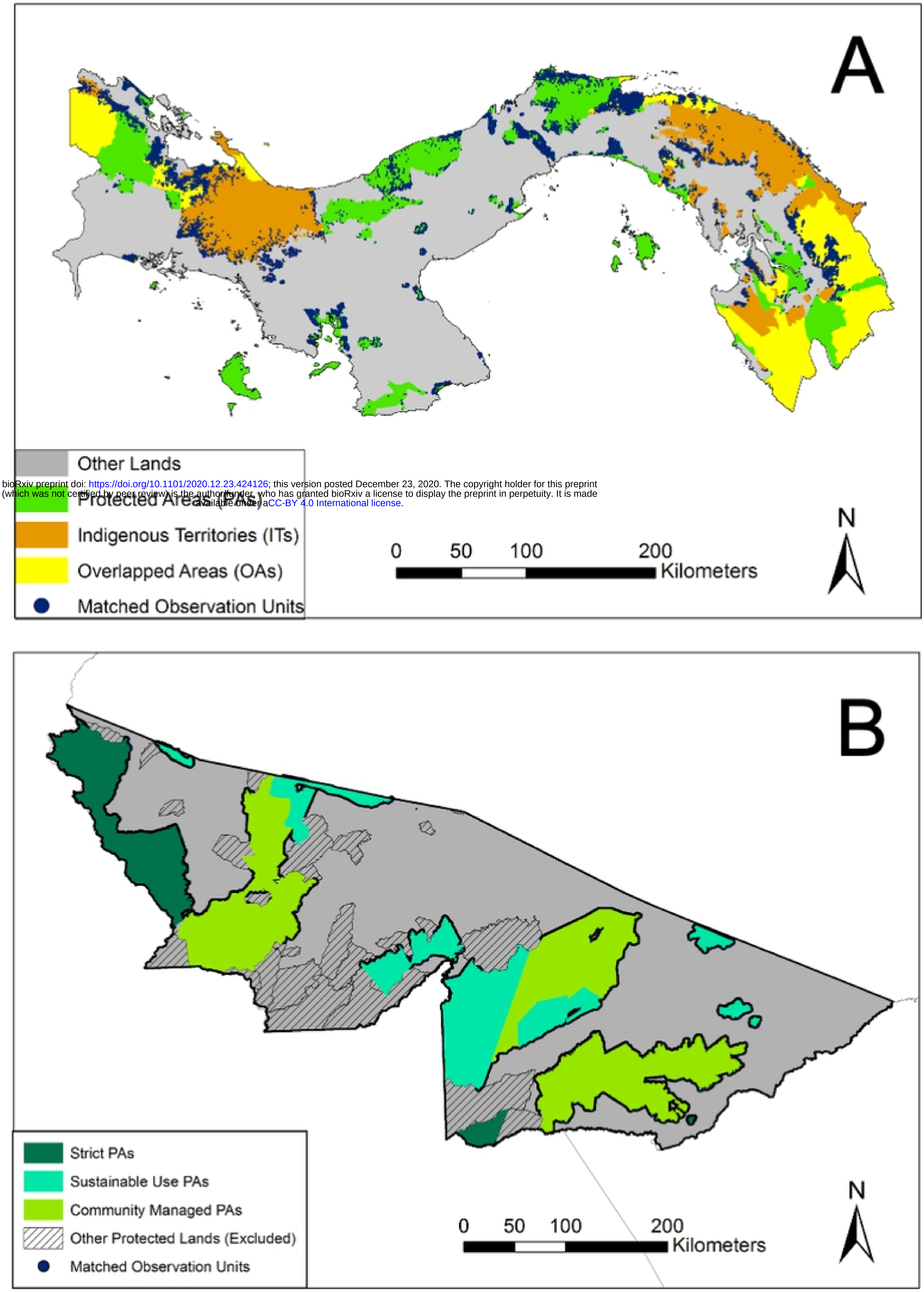
A
Other Lands
Protected Areas (PAs)
Indigenous Territories (ITs)
Overlapped Areas (OAs)
Matched Observation Units
0
50
100
200
Kilometers
N
B
Strict PAs
Sustainable Use PAs
Community Managed PAs
Other Protected Lands (Excluded)
Matched Observation Units
0
50
100
200
Kilometers
N

Fig 6

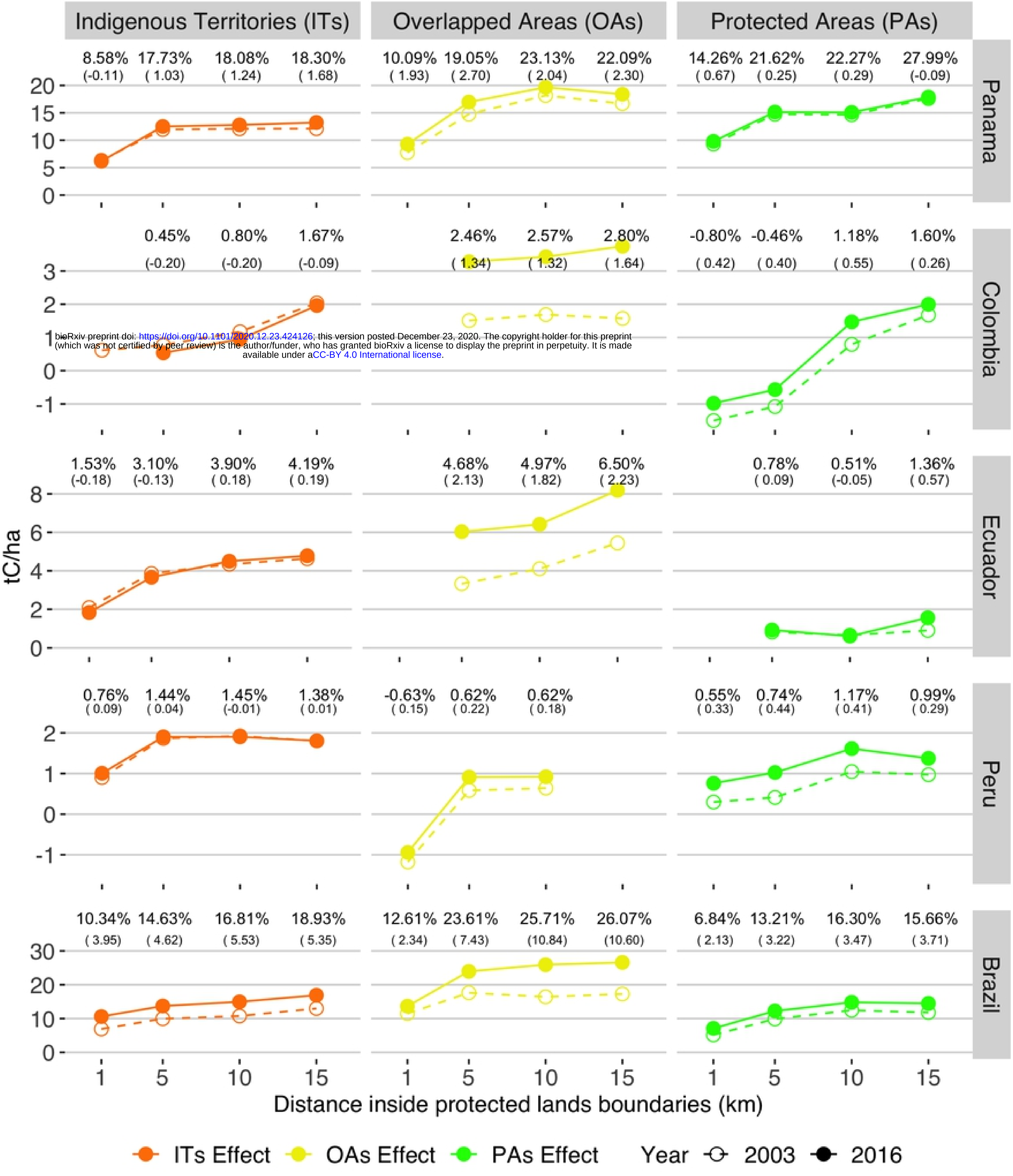
Indigenous Territories (ITs)
Overlapped Areas (OAs)
Protected Areas (PAs)
Panama
8.58% (-0.11) 17.73% (1.03) 18.08% (1.24) 18.30% (1.68)
10.09% (1.93) 19.05% (2.70) 23.13% (2.04) 22.09% (2.30)
14.26% (0.67) 21.62% (0.25) 22.27% (0.29) 27.99% (-0.09)
0 5 10 15 20
Colombia
0.45% (-0.20) 0.80% (-0.20) 1.67% (-0.09)
2.46% (1.34) 2.57% (1.32) 2.80% (1.64)
-0.80% (0.42) -0.46% (0.40) 1.18% (0.55) 1.60% (0.26)
-1 0 1 2 3
Ecuador
1.53% (-0.18) 3.10% (-0.13) 3.90% (0.18) 4.19% (0.19)
4.68% (2.13) 4.97% (1.82) 6.50% (2.23)
0.78% (0.09) 0.51% (-0.05) 1.36% (0.57)
0 2 4 6 8
Peru
0.76% (0.09) 1.44% (0.04) 1.45% (-0.01) 1.38% (0.01)
-0.63% (0.15) 0.62% (0.22) 0.62% (0.18)
0.55% (0.33) 0.74% (0.44) 1.17% (0.41) 0.99% (0.29)
-1 0 1 2
Brazil
10.34% (3.95) 14.63% (4.62) 16.81% (5.53) 18.93% (5.35)
12.61% (2.34) 23.61% (7.43) 25.71% (10.84) 26.07% (10.60)
6.84% (2.13) 13.21% (3.22) 16.30% (3.47) 15.66% (3.71)
0 10 20 30
tC/ha
1 5 10 15
Distance inside protected lands boundaries (km)
ITs Effect
OAs Effect
PAs Effect
Year
2003
2016

Fig 7

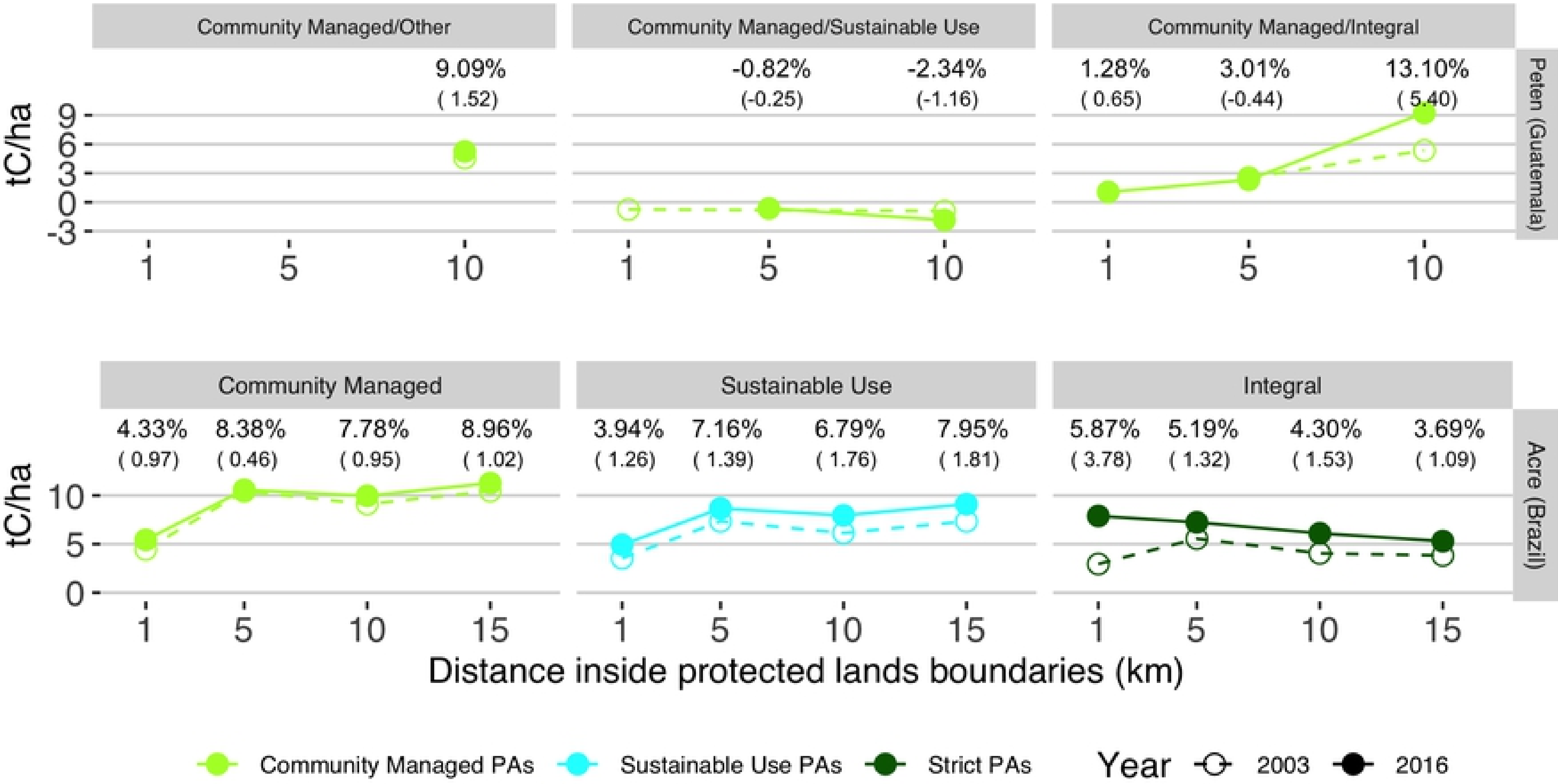
Community Managed/Other
Community Managed/Sustainable Use
Community Managed/Integral
Peten (Guatemala)
9.09%
(1.52)
-0.82%
(-0.25)
-2.34%
(-1.16)
1.28%
(0.65)
3.01%
(-0.44)
13.10%
(5.40)
tC/ha
9
6
3
0
-3
1
5
10
Community Managed
Sustainable Use
Integral
Acre (Brazil)
4.33%
(0.97)
8.38%
(0.46)
7.78%
(0.95)
8.96%
(1.02)
3.94%
(1.26)
7.16%
(1.39)
6.79%
(1.76)
7.95%
(1.81)
5.87%
(3.78)
5.19%
(1.32)
4.30%
(1.53)
3.69%
(1.09)
tC/ha
10
5
0
1
5
10
15
Distance inside protected lands boundaries (km)
Community Managed PAs
Sustainable Use PAs
Strict PAs
Year
2003
2016

Fig 8