The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas

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Maintaining the abundance of carbon stored aboveground in Amazon forests is central to any comprehensive climate stabilization strategy. Growing evidence points to indigenous peoples and local communities (IPLCs) as buffers against large-scale carbon emissions across a nine-nation network of indigenous territories (ITs) and protected natural areas (PNAs). Previous studies have demonstrated a link between indigenous land management and avoided deforestation, yet few have accounted for forest degradation and natural disturbances—processes that occur without forest clearing but are increasingly important drivers of biomass loss. Here we provide a comprehensive accounting of aboveground carbon dynamics inside and outside Amazon protected lands. Using published data on changes in aboveground carbon density and forest cover, we track gains and losses in carbon density from forest conversion and degradation/disturbance. We find that ITs and PNAs stored more than one-half (58%; 41,991 MtC) of the region's carbon in 2016 but were responsible for just 10% (−130 MtC) of the net change (−1,290 MtC). Nevertheless, nearly one-half billion tons of carbon were lost from both ITs and PNAs (−434 MtC and −423 MtC, respectively), with degradation/disturbance accounting for >75% of the losses in 7 countries. With deforestation increasing, and degradation/disturbance a neglected but significant source of region-wide emissions (47%), our results suggest that sustained support for IPLC stewardship of Amazon forests is critical. IPLCs provide a global environmental service that merits increased political protection and financial support, particularly if Amazon Basin countries are to achieve their commitments under the Paris Climate Agreement.

deforestation | forest degradation | forest carbon dynamics | Amazon | indigenous peoples

Improved land stewardship is central to achieving the climate change goals set forth in the Paris Agreement (1, 2), as well as to mitigate the projected impacts of a rapidly increasing global population on environmental sustainability and food security (3). Forest management represents low-hanging fruit, particularly as it relates to the conservation and restoration of tropical forest ecosystems. Significantly reducing carbon emissions from anthropogenic forest loss (i.e., deforestation and forest degradation) while increasing carbon uptake in places of prior loss (i.e., negative emissions through reforestation, restoration, or other management-driven activities) has the potential to offset as much as 60% of the emissions reductions needed to hold warming below the Paris Agreement goal of 2 °C (2).

While "natural climate solutions" hold great promise in theory, their practical implementation requires the identification of replicable models for on-the-ground interventions that are cost-effective, scalable, and have track records of success. In regions like the Amazon Basin, the contributions of indigenous peoples and local communities (IPLCs) to the conservation of tropical forests provide such a model. For millennia, Amazon IPLCs have served as the de facto guardians of what is now the largest remaining tract of tropical rainforest on the planet. Today, an estimated 1.7 million people belonging to some 375 indigenous groups live within ∼3,344 indigenous territories (ITs) and ∼522 protected natural areas (PNAs) (4) (*SI Appendix*, Table S1). Their territories span the eight nations (Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela) and one overseas territory (French Guiana) comprising the biogeographical limit of the Amazon (∼7.0 million km^2; Fig. 1). Amazon ITs alone cover nearly one-third (30%; including IT/PNA overlap) of the region's land area,

Significance

For decades, Amazon indigenous peoples and local communities (IPLCs) have impeded deforestation and associated greenhouse gas emissions. While emissions inside indigenous territories (ITs) and protected natural areas (PNAs) remain well below levels outside, unsustainable forest clearing is on the rise across the nine-nation region. In addition, Amazon ITs and PNAs are increasingly vulnerable to the less conspicuous (and often-neglected) processes of forest degradation and disturbance, which diminish carbon storage and ecological integrity. The trend toward weakening of environmental protections, indigenous land rights, and the rule of law thus poses an existential threat to IPLCs and their territories. Reversing this trend is critical for the future of climate-buffering Amazon forests and the success of the Paris Agreement.

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Data deposition: Spatial and tabular data central to this analysis are available at Woods Hole Research Center's GitHub repository (https://github.com/whrc/Amazon-Indigenous-Carbon).

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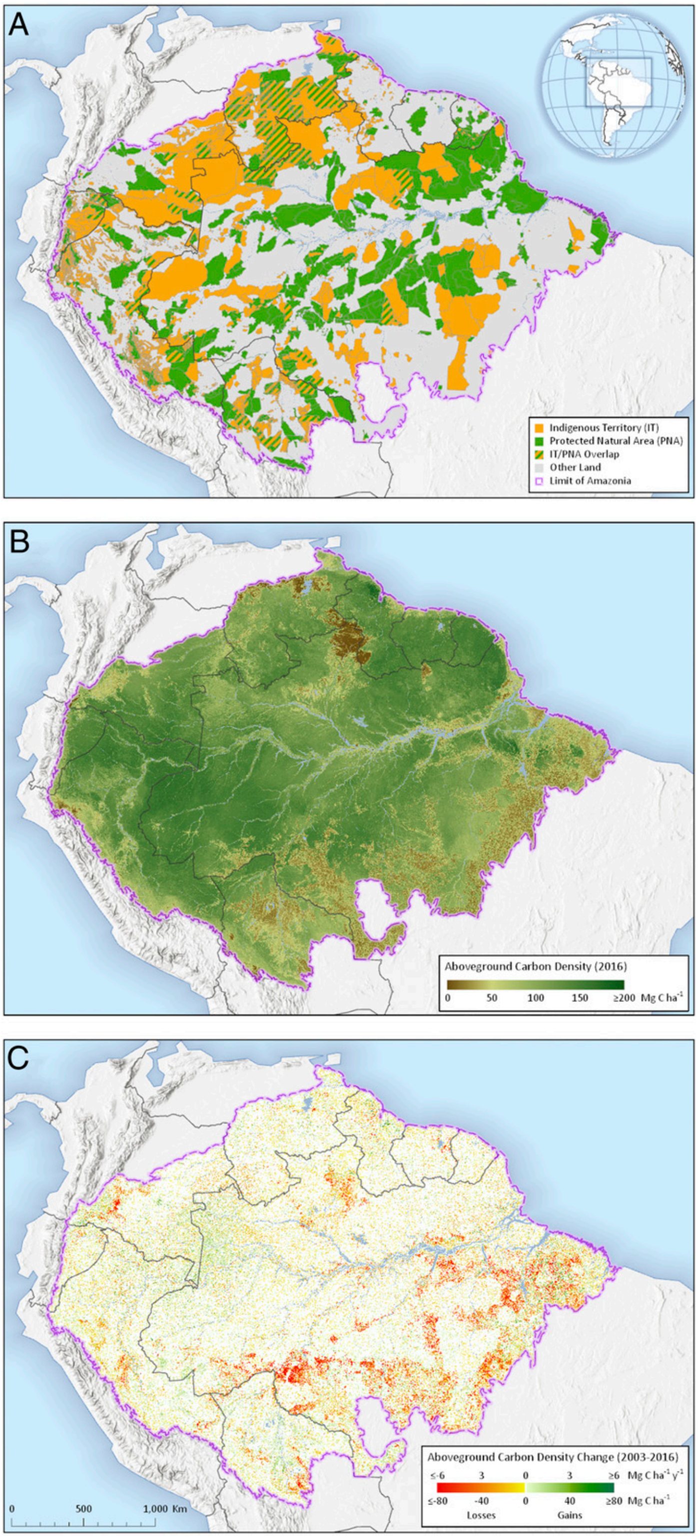

Fig. 1. The Amazon Basin. Distribution (ca. 2016) of ITs (orange) and PNAs (green) across the nine-nation region contained within the biogeographic limit of the Amazon (dashed purple line) (*A*) relative to the amount and distribution of aboveground carbon stocks (ca. 2016) (*B*) and changes (2003 to 2016) in aboveground carbon stocks (*C*).

and together with PNAs (22%) protect more than one-half (52%) of the Amazon rainforest (*SI Appendix*, Table S1).

Unlike PNAs, whose main purpose is biodiversity conservation, ITs are intended to safeguard the rights of indigenous peoples to their land and livelihoods for social, cultural, and equity reasons (5). IPLCs tend to value diversified resource bases that allow them to avoid dependence on markets for subsistence (6). As a result, their land use practices are often more holistic, combining traditional ways of life with modern perspectives on sustainable use. Their conservation efforts also tend to be more effective and less expensive than conventional government-sponsored alternatives (7, 8). Nevertheless, the rights of IPLCs to the land they occupy and the resources they depend on remain ambiguous and insecure across much of the region. Whereas nearly 87% of ITs (~79% by area) have some form of legal recognition (*SI Appendix*, Table S1), government concessions for mining and petroleum extraction overlap nearly one-quarter (24%) of all recognized territorial lands, substantially increasing their vulnerability to adverse impacts (9). Recent sociopolitical upheavals in Brazil, Colombia, and Venezuela have exacerbated the situation by weakening environmental protections, indigenous land rights, and the rule of law. These events pose an existential threat to IPLCs and their territories, suggesting that legal recognition may no longer be sufficient to safeguard the rights of forest-dwelling peoples across the region.

A growing body of evidence accumulated over the last decade suggests that IPLCs play a measurable and significant role in keeping forests intact, thereby reducing forest carbon emissions and mitigating climate change (10). A number of studies have demonstrated that Amazon ITs act as buffers to outside pressures associated with frontier expansion, reducing deforestation (7, 11–14) and fire occurrence (15) compared with areas outside their borders. From 2000 to 2015, five times more deforestation occurred outside ITs and PNAs than inside their boundaries—despite the fact that these units collectively span more than one-half of the Amazon region (4). Another group of studies expanded on this line of research using rigorous quasi-experimental methods to control for observable and potentially confounding land characteristics, such as remoteness and population density (16–19). For example, Blackman and Veit (17) combined cross-sectional matching and regression analyses to estimate avoided deforestation (based on ref. 20) and carbon emissions (based on ref. 21) attributable to indigenous management. They found that IPLC land use practices reduced deforestation and associated carbon emissions in Bolivia (13 $MtCO_2$ avoided), Brazil (184 $MtCO_2$ avoided), and Colombia (8 $MtCO_2$ avoided) during the study period (2001 to 2013) but had no discernable effect in Ecuador.

Studies on the effectiveness of indigenous land management in mitigating climate change often focus on avoided deforestation. This is not surprising given the well-established practice of using changes in forest area as a basis for estimating carbon emissions. However, this approach ignores emissions from anthropogenic forest degradation and natural disturbance—loss processes that occur in the absence of land use change (i.e., the forest remains forest but with reduced aboveground carbon density) and are increasingly significant drivers of carbon emissions from tropical forests (22). It follows that a more complete analysis of forest carbon emissions could shed new light on the emerging narrative linking indigenous land management to the maintenance of Amazon forest cover and associated carbon stocks.

Here we provide a comprehensive accounting of the role that Amazon ITs and PNAs play in the aboveground carbon dynamics of the region. This analysis applies new data from the 2003 to 2016 timeframe (updating ref. 22) to compare changes in the amount and distribution of aboveground carbon stored inside Amazon ITs and PNAs with lands outside their boundaries. We combine these carbon density estimates with published data on forest cover loss (20) to disaggregate losses in forest carbon into those attributable to forest conversion (e.g., biomass removals associated with commodity-driven deforestation) (23) versus those stemming from forest degradation and disturbance (e.g., biomass reductions attributable to selective logging, drought, wildfire, etc.).

While indigenous land management of ITs has proven effective in preventing large-scale forest loss, much less is known about its capacity to inhibit forest degradation and disturbance, particularly given that IPLC management often includes limited extractive activities. Moreover, some PNA designations allow for timber removal, and still others permit traditional extractive activities (e.g., sustainable development reserves and extractive reserves in Brazil). Extraction for any purpose necessarily reduces local carbon storage, yet even degraded and disturbed forests continue to accrue carbon. Gains from growth can compensate for some or even all of observed losses when both processes are considered at the scale of individual conservation units. Given these complex dynamics, we also evaluate the net effect of changes in carbon storage, considering both carbon emissions (losses) and carbon sequestration (gains) inside and outside of ITs and PNAs.

Results

Aboveground Carbon Storage (2016). Amazon ITs and PNAs stored well over one-half (58%; 41,991 MtC) of the region's aboveground carbon in 2016, with more than one-third (34%; 24,641 MtC) stored in ITs alone (including IT/PNA overlap; Fig. 2 and *SI Appendix*, Table S2). The Brazilian Amazon—roughly 1.5 times larger than the Amazonian portions of the other eight nations combined—held just over one-half (51%) of the carbon stored in Amazon ITs (24,641 MtC; including IT/PNA overlap) and 30% of the carbon stored in ITs and PNAs combined (41,991 MtC).

Venezuela had the largest proportion (85%) of its carbon under protection with 74% in ITs alone (including IT/PNA overlap), followed by Ecuador (81%) and Colombia (73%) (Fig. 2 and *SI Appendix*, Table S2). In fact, seven of the nine countries—Guyana (18%) and Suriname (15%) notwithstanding—had at least one-half (>50%) of their carbon stored within ITs and PNAs. In absolute terms, however, the amount of carbon under protection varies considerably by country (*SI Appendix*, Fig. S1 and Table S2). Total area and carbon storage in ITs and PNAs differed by as much as two orders of magnitude between countries (e.g., 2,119,000 km^2 and 24,826 MtC in Brazil vs. 41,000 km^2 and 453 MtC in Guyana) (*SI Appendix*, Tables S1 and S2). The difference in carbon storage increases to four orders of magnitude when only ITs (including IT/PNA overlap) are considered. These variations reflect broad differences in the legal frameworks for forest protection across Amazonian nations, as well as the geographic distribution of Amazon forests (e.g., the Brazilian Amazon is ~50 times larger than the French Guianese Amazon) (*SI Appendix*, Fig. S1 and Table S1), indigenous peoples, and population centers.

Change in Aboveground Carbon Storage (2003 to 2016). Our analysis reveals that the Amazon was a net source of carbon to the atmosphere from 2003 to 2016, releasing 1,290 MtC (4,727 $MtCO_2e$) when both losses and gains are considered (Table 1). This is consistent with results reported by Baccini et al. (22) at regional (multinational) and continental (South America) scales. We found that losses in forest carbon were nearly twice as large as gains (−3,141 MtC vs. +1,851 MtC) (*SI Appendix*, Table S3). These "gross" estimates of loss and gain are inherently conservative, given that these processes occur at scales finer than the minimum mapping unit of our analysis (i.e., a 21.4-ha grid cell).

Lands outside ITs and PNAs (i.e., Other Land; Table 1) accounted for ~70% of total losses (−3,141 MtC) and nearly 90% of the net change (−1,290 MtC). Despite substantial gains (+1,025 MtC), carbon uptake compensated for less than one-half (47%) of the losses from Other Land. In contrast, ITs and PNAs accounted for just 10% of the net change, with 86% of losses (−956 MtC) offset by gains (+826 MtC) (*SI Appendix*, Table S3). Nevertheless, Other Land gained more carbon (+1,025 MtC) in absolute terms than ITs and PNAs (+826 MtC), which already stored well over one-half (57%) of the Amazon's aboveground

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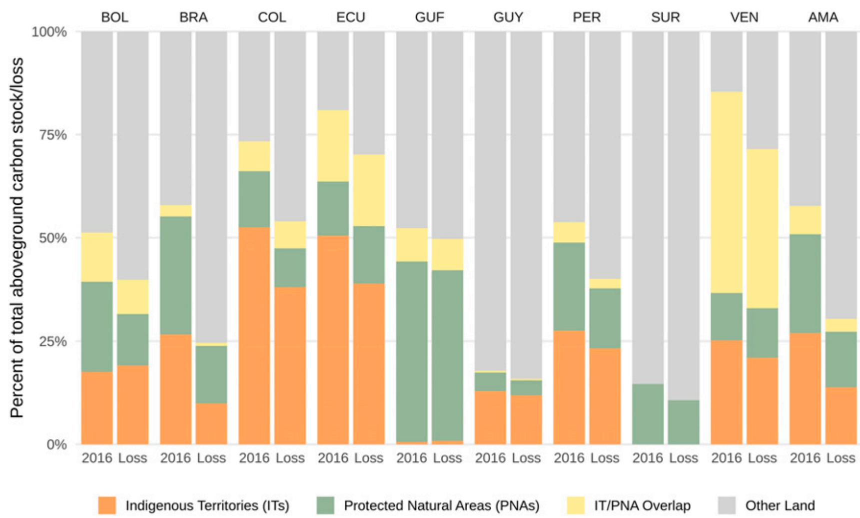

Fig. 2. Distribution of aboveground carbon stock (2016) and loss (2003 to 2016) by region (i.e., country/Amazonia) across ITs, PNAs, regions of IT/PNA overlap, and Other Land. Regions include the Amazonian portions of Bolivia (BOL), Brazil (BRA), Colombia (COL), Ecuador (ECU), French Guiana (GUF), Guyana (GUY), Peru (PER), Suriname (SUR), and Venezuela (VEN), as well as the whole of Amazonia (AMA). Stacked bars reflect the percentage contribution to the total stock (or loss) such that all bars sum to 100%.

woody carbon pool in 2003. Higher gains observed outside ITs and PNAs are likely attributable to forest regrowth in the Other Land category, which contains large expanses of degraded/secondary forest (<100 MgC ha^{-1}) (*SI Appendix*, Fig. S2*A*).

Considering land categories as independent carbon pools, we find that Amazon ITs (excluding IT/PNA overlap) experienced a 0.1% net change (−24 MtC) from 2003 to 2016, the smallest net loss of any land category (Fig. 3 and Table 1). By comparison, PNAs (excluding IT/PNA overlap) experienced a 0.6% net loss (−96 MtC) and Other Land exhibited a 3.6% net loss (−1,160 MtC) (Fig. 3 and Table 1). Nevertheless, over the 2003 to 2016 study period, total carbon losses approached one-half billion tons in both ITs (−434 MtC) and PNAs (−423 MtC) (excluding IT/PNA overlap); ITs exhibited a larger absolute loss and PNAs exhibited a larger relative net change (−0.6%). These results suggest that ITs and PNAs were (independently and collectively) more effective than Other Land in maintaining a balance between carbon losses and gains and thus in maintaining their overall stock of carbon intact.

At the country scale, our results reveal intrinsic spatial (Fig. 1*C*) and temporal (*SI Appendix*, Fig. S3) patterns reflecting a range of political, social, and environmental circumstances that interact in complex ways and at varying scales to drive subnational land-carbon dynamics. Not surprisingly, the Brazilian Amazon plays a central role in the trajectory of the region's forest carbon emissions (*SI Appendix*, Fig. S3), accounting for almost 90% (−1,154 MtC) of the observed net change from 2003 to 2016 (Table 1). Approximately 72% of region-wide losses occurred within Brazil, and these were offset by nearly 60% of region-wide gains (*SI Appendix*, Table S3). The vast majority of Brazil's net losses (89%) occurred outside ITs and PNAs (−5.4% in Other Land; Table 1); most of these changes occurred before 2008 and after 2012 (*SI Appendix*, Fig. S3). These findings are consistent with temporal trends in forest area change reported in previous studies (20, 24), as well as long-term deforestation monitoring by Brazil's National Institute of Space Research (25–27) (*SI Appendix*, Fig. S4)

Outside Brazil, no country was responsible for more than 2.5% of the region's total net change. Bolivia and Colombia were the second (−30.5 MtC) and third (−28.0 MtC) largest contributors, respectively, yet together they accounted for less than 5% of the net loss (only 7% of which was associated with ITs and PNAs). While the gap separating Brazil from the other eight countries is significant in absolute terms (reflecting Brazil's outsized land

Table 1. Net change (2003 to 2016) in carbon stock (MtC) inside ITs and PNAs vs. outside these units (Other Land) across the nine-nation Amazon study region (Fig. 1)

Unit	BOL	BRA	COL	ECU	GUF	GUY	PER	SUR	VEN	AMA
ITs	−8.7	−6.8	−1.2	−3.0	0.0	−0.5	−3.2	0.0	−0.2	−23.6
	−1.3%	−0.1%	0.0%	−0.5%	−0.2%	−0.2%	−0.1%	0.0%	0.0%	−0.1%
PNAs	6.3	−115.5	3.4	0.8	−0.2	−0.2	12.8	−0.2	−3.6	−96.4
	0.8%	−0.9%	0.4%	0.5%	0.0%	−0.2%	0.6%	−0.1%	−0.7%	−0.6%
IT/PNA overlap	−1.2	−2.4	−2.7	−0.9	−0.2	0.0	3.2	0.0	−6.2	−10.3
	−0.3%	−0.2%	−0.7%	−0.4%	−0.2%	0.4%	0.7%	0.0%	−0.3%	−0.2%
IT/PNA total	−3.5	−124.7	−0.5	−3.1	−0.4	−0.7	12.9	−0.2	−10.0	−130.3
	−0.2%	−0.5%	0.0%	−0.3%	−0.1%	−0.1%	0.3%	−0.1%	−0.3%	−0.3%
Other land	−26.9	−1,029.1	−27.5	−2.8	−1.0	−12.5	−39.3	−11.3	−9.3	−1,159.6
	−1.5%	−5.4%	−1.8%	−1.2%	−0.2%	−0.6%	−0.9%	−0.7%	−1.4%	−3.6%
Total	−30.5	−1,153.8	−28.0	−5.9	−1.3	−13.2	−26.4	−11.5	−19.3	−1,289.9
	−0.8%	−2.6%	−0.5%	−0.5%	−0.1%	−0.5%	−0.3%	−0.6%	−0.4%	−1.7%

Percentages reflect the change in carbon stock within each land category during the study period (i.e., relative to the 2003 baseline).

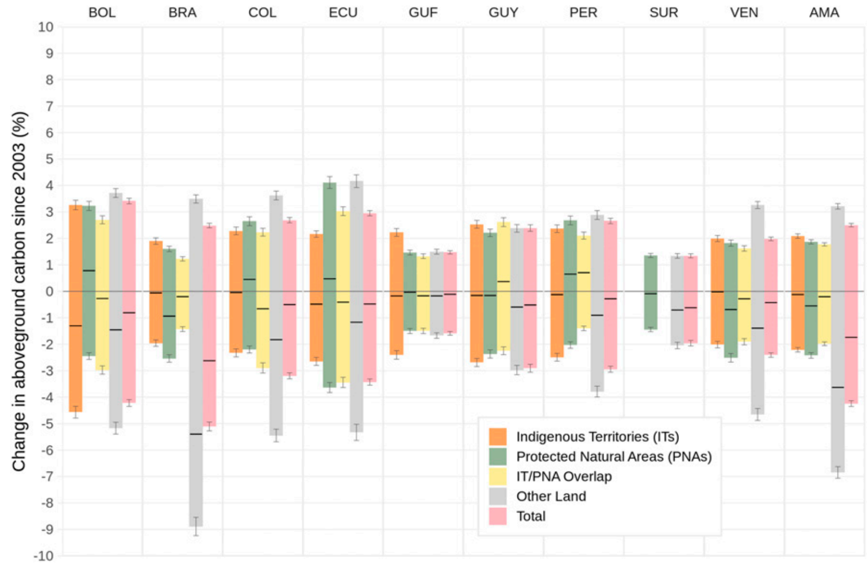

Fig. 3. Estimates of carbon loss (negative values), carbon gain (positive values), and the net change in carbon (bold black lines) during the 2003 to 2016 period of study as a percentage of the total stock present in 2003 across Amazon ITs, PNAs, regions of IT/PNA overlap, and Other Land. Error bars reflect the 95% confidence interval for the change (loss/gain) value (*SI Appendix*, Table S8).

area and standing carbon stock), the differential is perhaps best evaluated by considering each country's individual performance in maintaining its own aboveground carbon store. By this measure, Brazil registered a net loss of 2.6% from 2003 to 2016 (the largest proportion of any country), with Bolivia and Suriname a distant second and third, with net losses of 0.8% and 0.6%, respectively (Table 1).

Across countries and land categories, the net change in carbon is best understood relative to the initial standing stock in 2003 (Fig. 3). Viewed through this lens, we found Other Land to be the largest net source of carbon (−0.7 to −5.4%) of the four land categories in all but one country (Table 1). In other words, unprotected lands were the least effective at maintaining carbon stocks during the study period. By comparison, ITs and PNAs (individually and collectively) were more successful in maintaining carbon stocks across all nine countries. Generally speaking, ITs and PNAs were found to be at or near net zero (Fig. 3), ranging from a small net source in Brazil (−0.5%) to a small net sink in Peru (+0.3%), with the overall distribution skewed toward net sources (Table 1). In four of the nine countries (Bolivia, Colombia, Ecuador, and Peru), PNAs (excluding IT overlap) were a net carbon sink (+0.5 to +0.8%); however, the modest net source attributed to Brazil's PNAs (−116 MtC) more than negated the relatively small net sink (+23.3 MtC) from PNAs in four of the other countries (Table 1).

We recognize that ITs and PNAs have important differences in land management and utilization practices, whether among countries or across units within a category. Brazil and Peru, together encompassing more than 70% of the region's area, illustrate how these differences drive carbon density trends. Brazil's PNAs can be divided into those providing strict protection and those allowing for sustainable use (e.g., environmental protection areas, extractive reserves, and sustainable development reserves). The Chico Mendes Extractive Reserve in the State of Acre is perhaps one of the best-known sustainable use areas. This ~935,000-ha reserve is managed by traditional populations (historically rubber tappers), whose livelihoods are based on extractivism (rubber, Brazil nuts), subsistence agriculture (cassava, rice, beans), and livestock (cattle, poultry, pigs) (28). Our results indicate that sustainable use PNAs (excluding IT/PNA overlap) were responsible for more than 90% of the net losses (−105 MtC) attributed to Brazil's PNAs (−116 MtC) and nearly three times the total loss (−234 MtC) of strict protection PNAs (−79 MtC), which prohibit extractive activities (*SI Appendix*, Table S4 and Fig. S5). Whereas strict protection PNAs had relatively balanced carbon dynamics (i.e., losses of 79 MtC vs. gains of 68 MtC), sustainable use PNAs exhibited greater imbalance, with losses (−234 MtC) outpacing gains (130 MtC) by nearly 2:1 (*SI Appendix*, Table S4). While sustainable use resulted in higher losses than strict protection as a percentage of the 2003 baseline (−1.3% vs. −0.2%, respectively), the net loss of carbon under a sustainable use regime is still more than four times lower than that observed on other land (−5.4%).

Peru's ITs are classified as officially recognized, not officially recognized, reservations/intangible zones, and proposed reservations. Our results show that officially recognized ITs (ORITs), which account for almost 73% of the IT area in Peru, were responsible for 78% (−50 MtC) of the country's IT losses (−64 MtC) (*SI Appendix*, Table S5 and Fig. S6). Nevertheless, the majority of these losses (88%) were offset by gains (44 MtC) realized within ORITs. Indigenous reservations and proposed indigenous reservations—generally larger and more remote than ORITs—were found to be a net carbon sink on the order of 2.8 MtC. This net sink offset nearly one-half (47%) of the net source (6.0 MtC) attributable to ITs with and without official recognition (*SI Appendix*, Table S5).

Drivers of Aboveground Carbon Loss (2003 to 2016). Although ITs and PNAs were more effective than Other Land in maintaining carbon stocks during the study period, they were not impervious to losses. To understand why, we evaluated some of the underlying processes driving emissions inside and outside protected lands. We found that region-wide losses in carbon were almost evenly split between those attributable to forest conversion (FC; 53%) and those due to forest degradation and disturbance (D/D; 47%) (*SI Appendix*, Table S6 and Fig. 4). Carbon losses inside ITs and PNAs were driven primarily by D/D (75%), whereas losses outside protected lands were more commonly associated with FC (66%). Within ITs (including IT/PNA overlap), the proportion of losses associated with D/D increased to 82% (*SI Appendix*, Table S6 and Fig. 4), with the balance (18%) attributed to FC. A little over a third (35%) of PNA losses (excluding

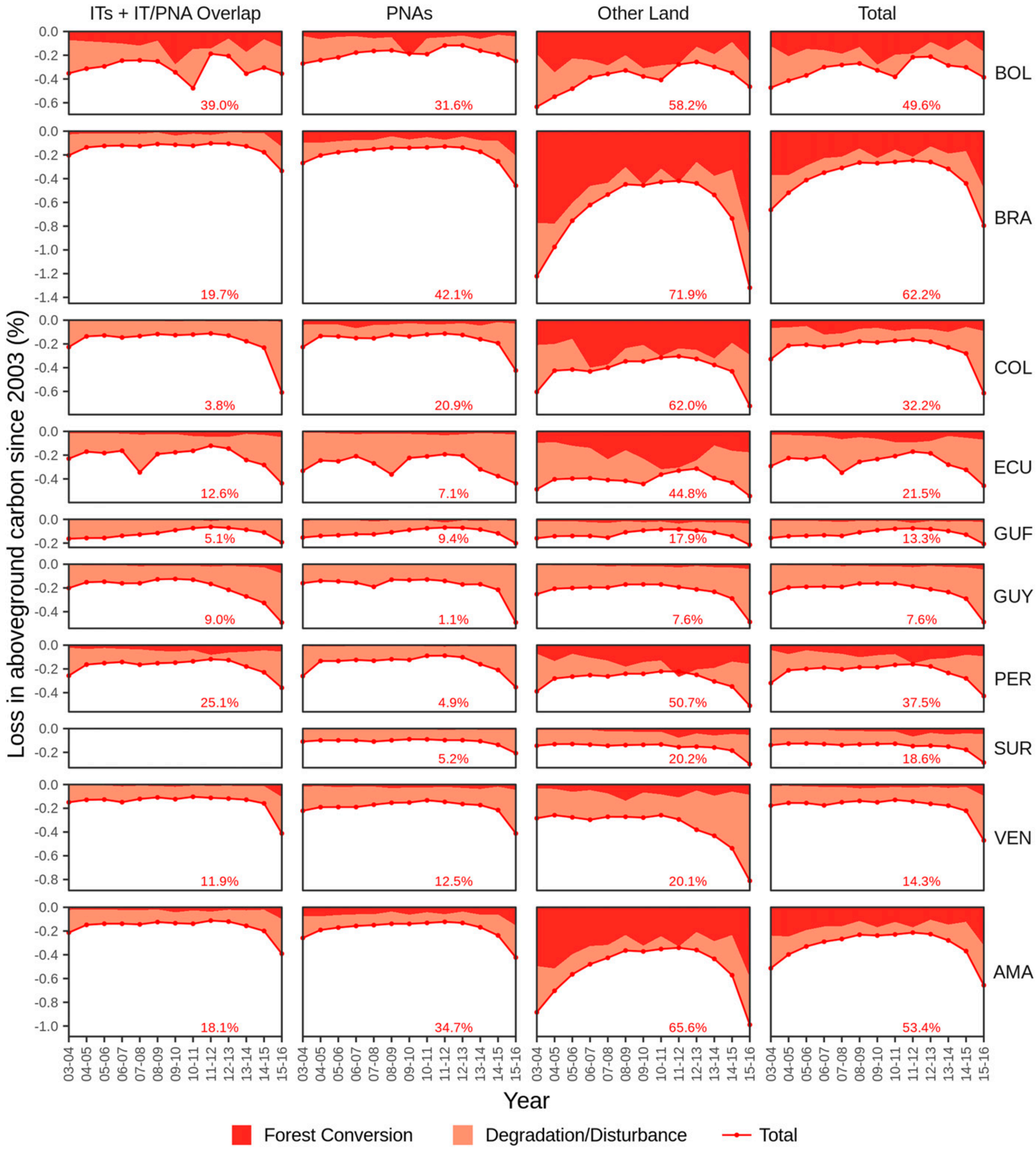

Fig. 4. Trajectories of annual loss (2003 to 2016) in aboveground carbon across ITs including the region of IT/PNA overlap, PNAs, and Other Land. Losses are disaggregated between those attributed to FC (biomass removal) vs. those attributed to D/D (biomass reduction). Values in red reflect the fraction of the total loss attributed to FC in each case.

IT/PNA overlap) were due to FC. Again, this larger fraction relative to ITs is likely due to the inclusion of PNA designations in Brazil that permit extractive activities (*SI Appendix*, Fig. S5 and Table S4).

Our results show that the proportion of total carbon loss attributed to FC versus D/D varied considerably at the national level, ranging from 2:1 in Brazil to 1:1 in Bolivia, 1:4 in Ecuador, and 1:12 in Guyana (Fig. 5). In short, FC played a much larger role in the loss of forest carbon stocks in Bolivia and Brazil compared with Ecuador and Guyana, where D/D drove upward of 80% of the total loss. Nevertheless, FC in ITs and PNAs was consistently low, responsible for less than 10% of total carbon

	CARBON LOSS (%)							
	FOREST CONVERSION				DEGRADATION / DISTURBANCE			
	INSIDE			OUTSIDE	INSIDE			OUTSIDE
	ITs	PNAs	Overlap	Other Land	ITs	PNAs	Overlap	Other Land
BOL	8	4	2	35	11	9	6	25
BRA	2	6	0	54	8	8	1	21
COL	2	2	0	29	36	7	6	18
ECU	7	1	0	13	32	13	17	17
GUF	0	4	0	9	1	37	8	41
GUY	1	0	0	6	11	4	0	78
PER	6	1	0	30	17	14	2	30
SUR	0	1	0	18	0	10	0	71
VEN	2	1	5	6	19	11	34	23
AMA	3	5	0	46	11	9	3	24

Fig. 5. Amazonian carbon loss and its attribution. Rows correspond to a region (i.e., country/Amazonia), and columns refer to a land category (i.e., ITs, PNAs, IT/PNA overlap, and Other Land). Cell values (%) in each row represent the loss fraction in that category and sum to 100%; cell temperature (i.e., darker shades of red correspond to higher temperatures) increases with increasing loss fraction. The left half of the matrix, which illustrates losses from forest conversion, reveals a clear contrast between relatively high temperatures outside of protected lands and very low temperatures inside. The right half of the matrix, which summarizes losses from degradation and disturbance, is distinguished by warmer temperatures overall but lacks a clear pattern of attribution among land categories.

losses in eight of nine Amazon countries (Fig. 5). Conversely, D/D in ITs and PNAs contributed substantially to carbon losses at the national level, accounting for more than one-third of losses (33 to 64%) in five of nine countries. Nearly one-half (49%) of Ecuador's carbon losses can be attributed to D/D within ITs (including IT/PNA overlap). This is the largest fraction of any country, likely due in part to the fact that nearly one-half of Ecuador's ITs (48% by area including IT/PNA overlap) overlap active petroleum concessions containing at least one well site (9, 29). Oil access roads in the Ecuadorian Amazon are documented drivers of forest loss, including degradation associated with subsequent colonization and illegal logging (30–33).

ITs and PNAs proved to be the most effective barriers to FC among all land categories. From 2003 to 2016, losses from clearing were 5 to 18% of IT and PNA losses in seven of the nine countries (*SI Appendix*, Table S6). Conversely, D/D was the clear driver of carbon loss (63 to 95%) inside protected lands. While the underlying causes are varied, illegal resource extraction (34–36), climate-induced droughts, and wildfires (37–41) likely play outsized roles. Many of these threats appear to originate outside ITs and PNAs, but these dynamics demand further study.

Our results were less consistent for the Other Land category. FC dominated losses (>50%) in four of the nine countries (Bolivia, Brazil, Colombia, and Peru), while D/D dominated losses (>75%) in four of the remaining five (French Guiana, Guyana, Suriname, and Venezuela) (*SI Appendix*, Table S6). Ecuador was the only country for which losses outside ITs and PNAs were split between FC (45%) and D/D (55%). Alarmingly, the trajectories of carbon loss from 2003 to 2016 reveal marked increases late in the time series (2012 to 2016; Fig. 4). This general trend is repeated across countries and land categories, especially outside of ITs and PNAs, and is particularly evident at the scale of the Amazon. These results are consistent with recent reports of marked increases in deforestation in Brazil (26, 27) and elsewhere across the region (34, 42, 43).

Carbon Density as an Indicator of Forest Intactness. The density of woody carbon on the landscape (MgC ha^{-1}), defined as the spatial distribution of carbon stored aboveground in the woody tissues of trees and shrubs, can serve as a simple (albeit imperfect) proxy for forest integrity or intactness (44). All else being equal, intact forests are expected to have a higher carbon density than degraded or disturbed forests. This is not always the case, given that carbon density is an integrated expression of a suite of anthropogenic (e.g., forest conversion, degradation, disturbance) and natural (e.g., geological, ecological) processes (45, 46). Although the vast majority of the study region (93%) falls within the tropical and subtropical moist broadleaf forest biome (47), variability within the biome (e.g., climatic, latitudinal, altitudinal gradients) exerts a strong influence on productivity and associated carbon accumulation (45). Nevertheless, we found the impact of human activity on the region's carbon storage capacity to be widespread, pronounced, and clearly discernable against the background of biogeographic variation.

Overall, ITs (excluding IT/PNA overlap) had the highest carbon density of any land category, averaging 116 MgC ha^{-1}, which is 26% higher than Other Land (92 MgC ha^{-1}) and 12% higher than the region-wide average of 104 MgC ha^{-1} (*SI Appendix*, Table S7). We observed a similar relationship in six of the nine countries, where carbon density was 8 to 37% higher inside ITs than outside. Brazil exhibited the largest disparity in carbon density, with 118 MgC ha^{-1} inside ITs (excluding IT/PNA overlap) vs. 86 MgC ha^{-1} outside (*SI Appendix*, Table S7).

While these differences in carbon density cannot be attributed solely to anthropogenic processes (i.e., forest loss in all its forms), the patterns observed are consistent with trends in carbon loss documented across the region (*SI Appendix*, Table S3). Forest conversion, the primary driver of carbon loss outside ITs and PNAs, involves the complete removal of aboveground biomass. Thus, FC tends to drive significantly greater reductions in average carbon density than D/D per unit area. It is no coincidence that in most Amazon countries, the Other Land category exhibits relatively high carbon loss and associated low carbon density due to the prevalence of FC. Regardless of whether the driver of loss is forest conversion, degradation, or disturbance, decreases in carbon density serve to compromise overall forest integrity and intactness.

Discussion

Our results reinforce the growing body of research showing that indigenous land tenure and management are key to safeguarding Amazonian forests against increasing demands for the region's land, energy, and mineral resources. In doing so, Amazon IPLCs have helped secure globally important stores of forest carbon and a range of critical ecosystem services. Amazon ITs and PNAs have contributed measurably to maintaining the integrity of the region's tropical forests while avoiding carbon emissions from deforestation and forest degradation. From 2003 to 2016, more than twice as much carbon was lost outside of ITs and PNAs (−2,185 MtC) as inside (−956 MtC), even though ITs and PNAs represented more than one-half of the region's land area (52%) and carbon stock (57%) in 2003 (*SI Appendix*, Tables S1–S3). Accounting for carbon uptake revealed a nearly nine-fold difference in net carbon losses outside ITs and PNAs (−1,160 MtC) versus inside (−130 MtC) (Table 1). While our analysis did not control for potential confounding land characteristics such as remoteness or population, our findings are consistent with studies that have. Blackman and Veit (17) found that IPLC management reduced deforestation and associated carbon emissions in Bolivia, Brazil, and Colombia, which together account for almost 75% of the region's land area and 72% of its carbon (*SI Appendix*, Tables S1 and S2).

Our results also shine light on a disturbing trend: Amazon deforestation is on the rise, especially in Brazil, Bolivia, Colombia, Ecuador, Peru, and Venezuela. Following a period of relative stability in the mid to late 2000s (27, 34, 43, 48), we observe a 200% increase in Amazon-wide carbon loss from 2012 to 2016 (*SI Appendix*, Fig. S3). In contrast to previous studies, our approach provides a comprehensive, region-wide accounting of net forest carbon emissions, taking into consideration biomass removals (deforestation), biomass reductions (degradation and disturbance), and biomass gains. This more nuanced understanding reveals an emissions source nearly twice as large as previously recognized, with Amazon-wide losses from degradation and disturbance (−1,463.7 MtC) accounting for nearly one-half (46.6%) of the estimated total (−3,140.7 MtC).

The impact of degradation and disturbance is more acute where Amazon indigenous territories are concerned. These processes were responsible for the vast majority of carbon losses inside ITs (>75% excluding IT/PNA overlap) in seven of the eight countries where ITs are recognized. By comparison, losses from forest conversion were modest, and total losses inside ITs were considerably lower than losses outside (with almost 90% offset by gains). Nevertheless, ITs still represented a small net source of carbon to the atmosphere (−23.6 Mt; −0.1%), with net losses observed in all 8 countries (led by Bolivia, with −8.7 MtC).

The presence of forest degradation and disturbance throughout the Amazon serves as a reminder that not all areas classified as "forest" are necessarily healthy or effective carbon sinks, and new tools and techniques are needed to better monitor and ultimately manage forest functional health and structural integrity. In many cases, the drivers of forest degradation originate outside protected lands, yet cascading effects can result in impacts experienced inside their borders. Disturbances linked to climate change can have particularly widespread effects that transcend administrative boundaries, while the institutions that enforce them are ill-equipped to respond to the growing threat. For example, increases in the frequency and extent of extreme droughts across parts of Brazil have increased tree mortality and with it the probability of wildfire. In the Xingu and Raposa Serra do Sol ITs, climate-induced tree mortality (49) has increased forest susceptibility to wildfires (38), leading to further increases in mortality and vulnerability to future droughts and other natural disturbances (41, 50).

Our research emphasizes the importance of considering scale in analyses of forest carbon dynamics in general and across the Amazon specifically. The vast majority of studies, including this one, are conducted at spatial scales ranging from thousands to millions of square kilometers. Yet regional changes in aboveground carbon storage reflect the net effect of many interacting local processes – natural and anthropogenic, social and political – whose impacts on a landscape are better understood when viewed through the lens of local people and places. Case studies (e.g., *SI Appendix*, Figs. S7 and S8) can provide valuable insights into the local circumstances and specific drivers that underlie the regional trends documented here.

The breadth and complexity of local processes affecting forest carbon dynamics underscore the need for further research on the attribution of forest conversion, degradation, and disturbance to specific drivers. A critical first step is the spatial disaggregation of carbon losses from natural disturbances and anthropogenic degradation. That alone would have far-reaching implications for protected area management, biodiversity conservation, and climate policy. More and better spatial data on the range of drivers (natural vs. anthropogenic, legal vs. illegal, etc.) and their distribution are also needed to improve attribution and inform forest management. Applying higher-resolution satellite data (e.g., 30-m Landsat imagery) to these analyses would further enhance driver attribution and reduce uncertainty in our estimates of carbon loss, particularly gross losses from degradation and disturbance. Progress in these areas could address a variety of compelling research questions: What is the contribution of climate-induced disturbance (e.g., drought) to Amazon carbon loss? Where are illegal activities (e.g., illegal logging, mining) driving carbon loss in protected lands? To what extent does anthropogenic degradation threaten Amazon forest integrity and carbon storage relative to natural disturbances? Answers to questions like these are key to the development of more effective resource management, law enforcement, and climate mitigation strategies.

Where efforts to mitigate global climate change are concerned, IPLCs have played an outsized role in limiting atmospheric emissions from forest loss by acting as barriers to deforestation in regions under pressure. The success of Amazon basin countries in achieving their nationally determined contributions (NDCs) to emissions reductions under the Paris Agreement will continue to depend in part on the ability of IPLCs to maintain Amazon forests intact. While most national forest monitoring systems track deforestation, they ignore forest degradation, due to the lack of robust operational approaches to detecting it. Our analysis is among the first to quantify degradation and disturbance using a coherent approach across all Amazon Basin countries and key land categories. The results suggest that a complete accounting of forest carbon emissions in these countries could lead to some, if not all, failing to meet their NDCs. This should be of particular concern to countries in which degradation and disturbance in protected lands represent a significant fraction of total carbon loss, including Colombia (50%), Ecuador (62%), and Venezuela (63%). For countries seeking to leverage the land use sector to meet their climate commitments, reducing emissions from deforestation and forest degradation (i.e., REDD+) remains low-hanging fruit.

In many respects, the outlook for Amazon forests and their continued stewardship by IPLCs is tied to the political and economic future of Brazil, which contains more than one-half of the region's protected lands (58%) and forest carbon (59%). Annual deforestation in the Brazilian Legal Amazon increased by 65% between 2012 and 2018 (from 4,571 km^2 to 7,536 km^2) (*SI Appendix*, Fig. S4). From 2016 to 2018 alone (i.e., the period following this study), deforestation in Brazil's ITs increased by nearly 150% (27). This reversal in the trajectory of deforestation tracks a period of erosion in governance (51), beginning with a controversial revision to Brazil's Forest Code in 2012. The revision granted amnesty to individuals accused of illegal deforestation before 2008 and reduced forest protections on private properties in Amazon states where >65% of the state's area is protected land (52, 48).

In early 2019, Brazilian President Jair Bolsonaro's newly established administration rolled back IPLC protections further by freezing the process of recognizing indigenous land rights, opening some ITs to agriculture and mining, and weakening government agencies charged with the management of ITs and PNAs (25, 53). In May 2019, Environmental Minister Ricardo Salles announced an overhaul of the rules governing project selection under the Amazon Fund, financed by Norway and Germany to support projects that reduce deforestation and support sustainable development. This action effectively paralyzed funds that provided crucial support to government agencies [e.g., Brazilian Institute for the Environment and Renewable Resources (IBAMA)] and actors charged with combatting illegal deforestation in protected lands. The administration's development-oriented policies have triggered a new wave of land grabbing and speculation, contributing to recent spikes in deforestation and widespread fires associated with land clearing (54). It remains an open question whether current policies—which have the potential to erase decades of progress in limiting forest loss, recognizing IPLC rights, and promoting sustainable development—can be swayed by economic incentives and/or political pressure to the contrary.

The research presented here supports an increasingly alarming narrative that points to a combination of interrelated factors—political upheaval, economic instability, market pressures, and climate change impacts—as responsible for the recent surge in forest loss across Amazonia. In absolute terms, current rates of loss pale in comparison to the levels observed at the turn of this century; nonetheless, Amazon indigenous communities and the forests on which they depend are at a critical juncture. The collective rights of IPLCs to their traditional lands, territories, and associated natural resources must be understood and respected as a fundamental human right. At the same time, indigenous land stewardship is a global environmental service that merits both political protection and financial support. Land rights and tenure security need to be strengthened and protected, whether through country-level programs (e.g., Socio Bosque in Ecuador, Amazon Fund in Brazil), regulatory frameworks, or international processes such as the Local Communities and Indigenous Peoples Platform of the United Nations Framework Convention on Climate Change (UNFCCC). In addition, there is an urgent need for nuanced policies that sustainably expand and accelerate opportunities for livelihood diversification while acknowledging the varying social and economic pressures that differentially threaten IPLCs across the range of occupied territories and reserves. Renewed regional efforts are also needed to strengthen law enforcement to prevent illegal extractive activities in and around ITs and PNAs. Finally, investment in state-of-the-art tools and techniques to facilitate the monitoring of forest degradation and disturbance is critical. Without measurement, there can be no management. IPLCs have a clear and present role to play in curbing global climate change; however, the permanence of this undervalued service depends on local, national, and regional recognition of the rights of forest-dwelling peoples to their land, as well as innovative policies that provide support for their traditional ways of life.

Materials and Methods

This analysis combines an update (2003 to 2016) to recently published data on changes in pantropical aboveground carbon density (ACD) with a comprehensive spatial database of IT and PNA limits, curated by the Red Amazónica de Información Socioambiental Georreferenciada [(RAISG) Amazon Georeferenced Socio-Environmental Information Network]. The database consists of information collected from a range of government and nongovernment

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sources and is updated annually to reflect changes (e.g., additions, deletions, and/or modifications) to the official status and/or spatial extent of individual units. This study relies on the 2016 database release (4). Surinamese IT units are absent from this release, because the Surinamese government affords no official recognition to indigenous or tribal communities and no legislation exists establishing or governing indigenous lands or other rights (55).

The study region is defined by the biogeographical limit of the greater Amazon ecosystem (Fig. 1). This boundary considers the functional and biotic relatedness of ecosystems classified as Amazonian forest by the nine nations and includes the forests of the Guiana Shield. Country limits were derived following adjustments to national borders based on geographic considerations. Such adjustments were necessary to address, in an unbiased fashion, the coarse nature of existing boundary databases as well as ongoing boundary disputes between countries. As a result, the limits used here are not strictly official.

We estimated ACD change (2003 to 2016) based on an update to ref. 22, which provided the first spatially explicit satellite-based estimates of net carbon emissions from tropical forests, including gains and losses in carbon density from 2003 to 2014, at ~500-m resolution. Carbon gains are a product of forest biomass accrual (i.e., growth), whereas losses are the result of biomass removals associated with forest conversion (e.g., deforestation) to an alternative land use or reductions in biomass density within a standing forest (i.e., anthropogenic degradation or natural disturbance). This approach combined field measurements with colocated NASA light detection and ranging (LIDAR) data to calibrate a machine-learning algorithm (56, 57) that generates spatially explicit annual estimates of aboveground live dry woody carbon density from 12 y (2003 to 2014) of NASA moderate-resolution imaging spectroradiometer (MODIS) satellite imagery at a spatial resolution of 463 m (21.4 ha). The 12-y time series was analyzed at the grid cell level with a change point-fitting algorithm to quantify losses and gains in carbon. The approach accounts for these changes without the need to explicitly define and/or identify their cause (e.g., changes in land use). Updates to the approach of ref. 22 included (*i*) migration from now decommissioned MODIS/Terra and Aqua Nadir BRDF-Adjusted Reflectance (NBAR) Collection 5 data to the equivalent Collection 6 (MCD43A4 V006) data (66 predictor variables); (*ii*) adding 67 WorldClim 1.4 climate variables reflecting current (~1960 to 1990) climatic conditions (58) and 59 SoilGrids soil variables (59) to the predictor stack; and (*iii*) extending the original 12-y time series (2003 to 2014) by 2 y (2003 to 2016).

We analyzed the four data sources described above (i.e., ACD change combined with region, national, and IT/PNA limits) using the R statistical software package with raster-based zonal statistics. The political/administrative limits provided the spatial basis for quantifying the amount and distribution of gains and losses in carbon observed inside and outside of ITs and PNAs across Amazonia during the 14-y (2003 to 2016) study period. Regions of IT and PNA overlap (Fig. 1*A*) were analyzed separately. For the purpose of this study, Other Land is defined as land lacking the formal protections associated with ITs and PNAs, which necessarily vary by country. As such, we recognize Other Land to be a broad and diverse category that is fundamentally distinct from ITs, PNAs, or their regions of overlap.

ACD losses inside and outside of ITs and PNAs were disaggregated into those attributable to complete biomass removal (e.g., forest conversion to agriculture following deforestation, referred to here as FC) and those attributable to biomass reduction (e.g., forest remaining forest—albeit degraded or disturbed—referred to here as D/D) following methods developed in ref. 22. The analysis was accomplished by combining the 30-m forest cover loss data of ref. 20 with 30-m ACD data for the year 2000 described by refs. 60 and 22. The 30-m ACD layer was generated using the 30-m Landsat inputs from ref. 20 together with the field calibration data used in generating the annual ACD change estimates reported here. Further information on the 30-m forest cover loss and ACD datasets can be found in refs. 20 and 60, respectively.

The steps used in apportioning ACD losses to FC or D/D are as follows: (1) using a GIS, we overlaid the 30-m forest cover loss data (20) on the 30-m ACD data (60); (2) for each 500-m MODIS grid cell exhibiting statistically significant loss in carbon density, we calculated the total aboveground carbon associated with forest cover loss from 2003 to 2016; (3) we then subtracted the estimated carbon loss attributable to FC (step 2) from the total carbon loss measured at the ca. 500-m scale (22) to estimate carbon loss from D/D. Steps 1 and 2 provide the most contemporary and robust estimate of ACD loss associated with forest conversion (e.g., deforestation) using data products designed to minimize spatial inconsistencies and inaccuracies. To the best of our knowledge, the result represents the only available estimate of region-wide loss in ACD attributable to forest conversion, degradation, and disturbance.

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