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Roads, deforestation, and the mitigating effect of protected areas in the Amazon

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ABSTRACT

Roads have a major impact on Amazon deforestation. However, the effects of the rapidly growing network of illegal or unofficial roads in the Amazon are usually not considered. We assessed relationships between past deforestation and existing networks of highways, navigable rivers, and all other roads, including more than 190,000 km of unofficial roads. We found that deforestation was much higher near roads and rivers than elsewhere in the Amazon; nearly 95% of all deforestation occurred within 5.5 km of roads or 1 km of rivers. Protected areas near roads and rivers had much lower deforestation (10.9%) than did unprotected areas near roads and rivers (43.6%). If one assumes that existing protected areas halt deforestation, then we estimate that 39,462 km^2 of expected forest clearing would have been avoided. However, if one assumes that protected areas merely displace deforestation to other locations, then we estimate that 34,501 km^2 of expected clearing would have been displaced elsewhere. We conclude that proximity to transportation networks, particularly the rapidly growing unofficial road network, is a major proximate driver of deforestation in Amazonia and that protected areas are having a strong mitigating effect on that risk.

1. Introduction

The Brazilian Amazon harbors one third of the world's tropical forests and has been estimated to sustain 13% of the world's biota (Lewinsohn and Prado, 2005). Moist, tropical forests in this region span across an area of roughly 4 million km^2, 90% of which was once forested (Olson et al., 2001). This region of rich biodiversity is also experiencing some of the world's highest deforestation rates, averaging 0.52% yr^{-1} (18,857 km^2 yr^{-1}) through the 1990s and 2000s (INPE, 2009). As of 2009, roughly 18% of forests had been converted to other land uses (Pereira et al., 2010), with an area likely larger than this 18% modified by selective logging, edge effects, surface fires, and hunting (Peres et al., 2006; Souza et al., 2005).

Throughout the tropics, major roads open up areas of forest to settlement and resource extraction (Laurance et al., 2009). In Amazonia, most deforestation has been found to occur in proximity to major roads. Alves (2002) reported that nearly 90% of deforestation occurred within 100 km of major roads. Additional studies, using 50 km as a baseline distance, have accounted for deforestation levels varying from 67% (Asner et al., 2006; Nepstad et al., 2001) to 85% (Chomitz and Thomas, 2001). However, defining regions of deforestation by such large (50 and 100 km) distances from major roads corresponds to 40% and 63% of the Amazon, respectively. Hence, these measures are imprecise and are only marginally predictive of deforestation. Despite this, it is clear that the transportation network will play a significant role in future forest clearing in the region (Fearnside, 2007; Fearnside and Graca, 2006; Kirby et al., 2006; Laurance et al., 2001, 2002).

In addition to major road networks, a network of unofficial roads, built without any government oversight or incentives, is rapidly growing in the Amazon region (Arima et al., 2005; Asner et al., 2006; Brandão and Souza, 2006; Perz et al., 2007). These roads are generally built to open up forests to exploitative activities such as logging but subsequently lead to new colonization (Veríssimo et al., 1995), forest fragmentation (Arima et al., 2008), ecological degradation (Laurance et al., 2006), and increased fire risk (Cochrane, 2003; Nepstad et al., 2001). Very high annual growth rates (exceeding 40 km of new roads per 10,000 km^2 of area) have been reported in some regions (Brandão and Souza,

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2006). Navigable rivers provide another potential mode of access to forested regions and further promote deforestation and logging (Peres and Terborgh, 1995; Veríssimo et al., 1998), although they are largely left out of region-wide analyses of deforestation drivers.

Brazil's extensive network of protected areas (PAs) was established to preserve priority biodiversity conservation areas, establish biodiversity corridors, and protect portions of the 23 Amazonian ecoregions identified by World Wildlife Fund – Brazil (Rylands and Brandon, 2005; Silva, 2005). By 2006, 1.8 million km^2, roughly 45% of Amazonian tropical forest, was under some level of protection as federal- or state-managed land or designated as indigenous reserve. Strictly protected areas, whose primary function is to conserve biodiversity, constitute only a modest fraction (19.2%) of the Amazon PA network. Federal and State sustainable use areas allow various levels of resource use and extraction, and make up 30.6% of the network. Indigenous reserves constitute the remainder; large-scale deforestation is prohibited in these lands and hence they also play an important role in protecting forests (Schwartzman and Zimmerman, 2005). The combinations of federal- and state-managed strictly protected areas, federal- and state-managed sustainable use areas, and indigenous lands constitute the 5 types of protection that were examined in this study.

Protected areas in the Amazon fall into two distinct classes; those currently under threat of unwanted forest loss or degradation due to human activities which need to provide an active resistance to development pressure; and those under no current pressure due to their remoteness and inaccessibility, thereby affording a default protection status (Adeney et al., 2009; Barber et al., 2012; Joppa et al., 2008). This dichotomy can confound aggregated assessments of entire PA network performance. A substantial area of protected forest is located far away from transportation networks and not easily accessible, and thus can be deemed "successfully protected" even though it has not been under any direct development pressure. Several studies have shown that the Amazonian PA network as a whole has been successful at resisting development pressure and forest clearing within protected boundaries (Barber et al., 2012; DeFries et al., 2005; Joppa et al., 2008; Nepstad et al., 2006), however there are individual PAs that have not demonstrated similar success (Barber et al., 2012; Pedlowski et al., 2005).

Roads strongly influence threats to protected areas. The protection afforded by reserves against deforestation fires has been assessed using major road networks (Adeney et al., 2009), as has projecting the future effects of conservation efforts (Laurance et al., 2001; Soares-Filho et al., 2006). PAs have been shown to substantially slow the expansion of unofficial roads (Brandão and Souza, 2006), but the effects of different reserve types on patterns and rates of deforestation fostered have not been closely examined. Here we used extensive information on transportation networks to assess the status of accessible protected forests. We assessed relationships between the extended transportation network (including unofficial roads and rivers) and deforestation, and then estimated the amount of deforestation that would occur in protected lands if not for their protected status. PAs impact deforestation by either outright preventing or avoiding it, or by displacing possible deforestation elsewhere into unprotected lands. We estimated the mitigating effect of PAs under both of these scenarios. Our findings have clear implications for managing and conserving Amazonian forests.

2. Data and methods

2.1. Study area and data

We examined the spatial relationships between the road/river transportation networks, deforestation, and protected areas within the Brazilian Amazon – defined here as the roughly 4 million km^2 of moist, tropical forest biomes delineated by the WWF Terrestrial Ecoregions (Olson et al., 2001). The network of official roads was sourced from the Instituto Brasileiro de Geografia e Estatística (IBGE) bCIMd dataset (IBGE, 2004) which included 73,553 km of roads in the region. A 22,713 km network of "highways" was extracted from this dataset based on the criteria of having federal or state highway designations. A dataset of unofficial roads for the entire region compiled by Instituto do Homem e Meio Ambiente da Amazônia (Imazon) was obtained (see Acknowledgements). This dataset contained unofficial roads mapped from Landsat imagery according to the method described by Brandão and Souza (2006) and included an additional 190,506 km. The majority of these unofficial roads were mapped from 2003 observations with minor updates in later years to 2007. These were combined with the complete IBGE dataset to create a 264,058 km network of "all roads". Preliminary analysis of a navigable rivers dataset (Veríssimo et al., 1998) in conjunction with these road networks revealed that greater than 40% of the region was closer to a navigable river than any type of road, we therefore included this navigable river dataset in subsequent analyses.

Areas of remaining forest and past land clearing activities were extracted from land cover data produced by Brazil's National Institute of Space Research (INPE), who have conducted mapping of Amazonian deforestation under the PRODES project (Monitoramento da Floresta Amazônica Brasileira por Satélite). PRODES has mapped past deforestation in the region since 1997, annually since 2000, using high-resolution satellite data from Landsat. The landcover data for 2006 were used to assess areas of remaining forest and past land clearing, up to and including 2006, at a grain size of 60 m. Water and other naturally occurring non-forest areas were reclassed to an "other" class, leaving "forest", "deforestation", and "other". These data were spatially subset to the boundaries of the moist, tropical forest biomes.

2.2. Transportation network influence

The a priori distances of 50 km and 100 km were used with the highway network to determine the overall proportion of the region defined by these distances for comparison with past studies, as described in Section 1. The Euclidian distance to the closest element of each transportation network (highways, all roads, and rivers) was calculated for every 60-m cell in the land cover data, out to an arbitrary maximum distance of 250 km, although it is highly unlikely that any influence exists at that maximum distance. The resulting distances were binned into 100-m distance classes and the fractional contribution of deforestation in each class with respect to all clearing in the region was calculated. Additionally, for the all roads network, the fraction of past land clearing in each class was calculated for both protected and unprotected land (Fig. 1).

We determined quantitatively the distance at which the influence of each transportation network on deforestation begins to diminish. This was calculated by plotting the curve of accumulated deforestation vs. distance and estimating the slope of the curve via a linear fit through 11 observations centered on each distance. The resulting value is correlated to the local rate of accumulation at any given distance with high values near the transportation networks (rapid accumulation) and low values at extreme distances (slow accumulation). The distance at which the slope changes from greater than one to less than one was determined to be the point where influence begins to diminish (Fig. 1). The fraction of total regional deforestation captured within this distance and the proportion of the overall region represented were also calculated (Table 1). The initial calculation using the same method for proximity to rivers (17.3 km) was considered to be unrealistic when

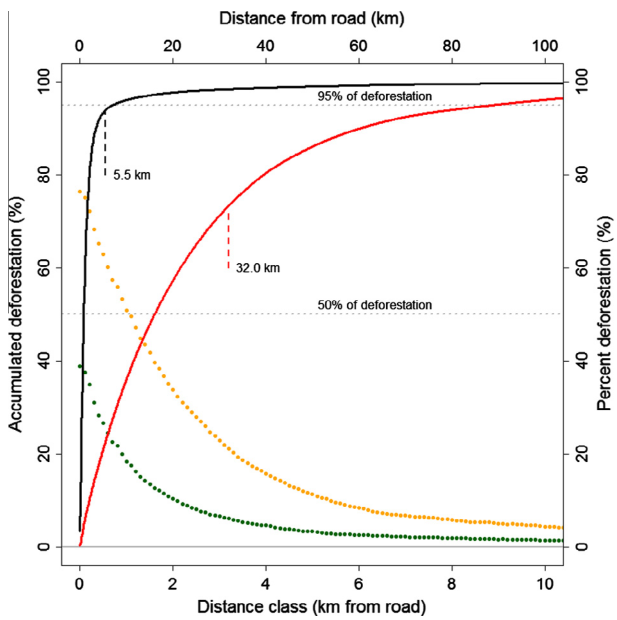

Fig. 1. Accumulation of overall deforestation with respect to distance from roads (left and top axes). Red line is distance to highway network indicating distance at which 95% of deforestation is accounted for and the calculated distance of diminishing influence. Black line indicates same for all official and unofficial roads. The percent deforestation within 100 m distance classes (bottom and right axes) shows relationship between deforestation in protected areas (green) and unprotected forests (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Calculated distances at which each network begins to have decreasing influence on accumulated deforestation, the total percent of Amazonian deforestation captured at that distance, and the proportion of the entire region represented.

	Distance (km)	Percent of deforestation (%)	Percent of region (%)
Highways	32.0	73.9	29.3
All roads	5.5	94.0	31.7
Navigable rivers	17.9	17.6	32.6
Alternate river distance	1.0	0.9	21.4

visually observing deforestation patterns within this riverine zone. Based on these observations, the distance of strong influence for rivers was set at 1.0 km. This distance was likely to include deforestation along waterways when accounting for seasonal water levels and tributary junctions with respect to navigable river boundaries, any deforestation greater than 1.0 km was expected to be related to a road that was not included in our database.

All areas with distances less than these threshold values were considered areas where proximity to the transportation network had a strong influence on deforestation. These areas for all roads and rivers were combined to determine the highly accessible zone throughout the region. Land cover was tabulated within this accessible zone by conservation status. Protected land was assessed in each of the five protected classes. The observed overall percent of forest clearing within distance classes was also determined for unprotected lands and all five types of PA.

2.3. Effects of protected areas

The impact that PAs have on the role of roads as a deforestation driver was examined under 2 differing scenarios within the highly accessible zone defined by the all roads network. Scenario 1, prevention of deforestation, assumes that in the absence of protection protected forests would experience the same trends in deforestation, with respect to accessibility, as unprotected lands. The fractions of forest clearing in each distance class observed in unprotected land were applied to protected forests, regardless of PA type, to determine the expected amount of deforestation. For example, Fig. 1 shows the first distance class in unprotected lands (adjacent to roads) to be roughly 78% deforested. This scenario would then assign 78% of the area adjacent to roads in PAs as deforestation. The difference between this estimate of expected and observed forest loss provides a measure of potentially *avoided* deforestation. This also assumes that the presence and/or role of PAs have no effect on unprotected forests and therefore the total area cleared in unprotected lands remains the same as observed. As a result, the total expected deforestation is greater than the observed under this scenario because the simulated deforestation in PAs is higher than the level observed, and in unprotected lands the level is unchanged.

Scenario 2, displacement of deforestation, assumes that the total amount of forest clearing within the region is fixed at the amount of observed deforestation. The total amount of deforestation observed in each distance class was redistributed evenly across all land regardless of protection status to estimate expected deforestation. For example, if the total land area represented by a given distance class was 50% located in unprotected land and 10% located in each of the five PA types, the total area of deforestation within that distance class would be redistributed according to those percentages. The difference between this estimate and observed clearing provides a measure of potentially *displaced* deforestation, clearing that likely would have occurred within PAs that has been relocated to unprotected land due to conservation designation. Since the overall amount of cleared forest is fixed in this scenario, the expected deforestation in unprotected lands is lower than that observed because more clearing would be expected in protected areas in the absence of protection.

3. Results

3.1. Highways as deforestation drivers

PRODES land-cover data indicate that 476,925 km^2 of forest within the Brazilian Amazon had been cleared up until 2006. Using these data, we assessed regions defined by both 50 and 100 km of highways for comparison with previous studies (Alves, 2002; Asner et al., 2006; Chomitz and Thomas, 2001; Nepstad et al., 2001). These regions encompass 40% and 63% of all land cover classes (Fig. 2a) and account for 85.5% and 95.5% of all cleared forest lands, respectively. As of 2006, there was 32,381 km^2 of cleared forests within boundaries of PAs. Only 52.6% of this was within 50 km of highways, 75.6% within 100 km. The calculated distance at which highways begin to have a rapidly diminishing influence was only 32.0 km, comprising less than 30% of the overall region and containing less than three fourths of observed deforestation (Table 1).

3.2. Land cover in the accessible zone

The calculated distance for diminishing influence for the combined official and unofficial road network (5.5 km) was combined with the assessed distance of riverine influence (1.0 km) to define the total zone of accessibility. This zone was approximately 1.4 million km^2, 35.2% of the Brazilian Amazon, and encompassed 94.9% of all deforestation (Fig. 2b). The total amount of remaining forest, past deforestation, and other land cover classes were quantified in the accessible zone and separated by conservation status as well as type of protected area (Table 2). Within this zone of accessibility, 19.2% of land fell within the borders of PAs encompassing 26.2% (196,845 km^2) of the remaining forest.

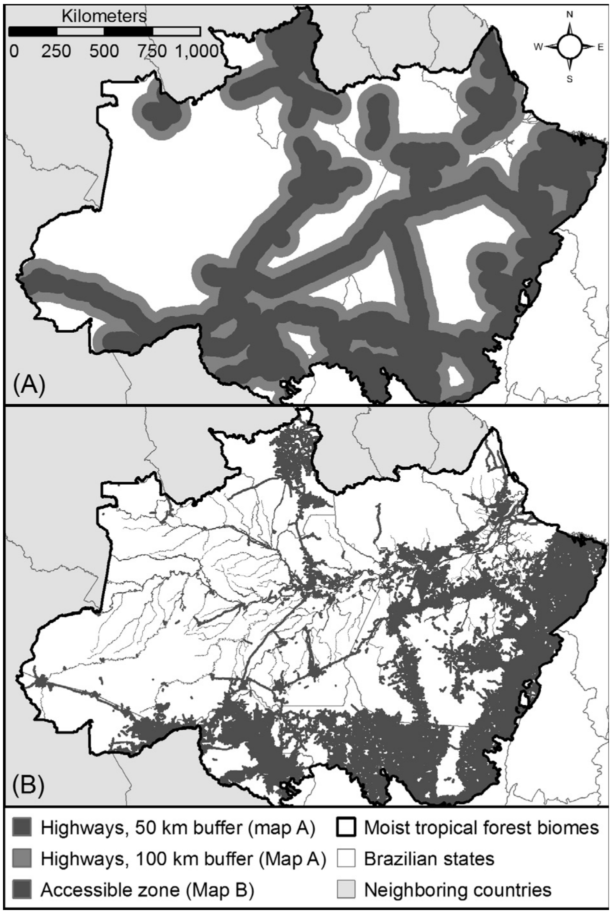

Fig. 2. (A) Commonly used 50 and 100 km distances from main roads represent 40% and 63% of the region, respectively. (B) Accessible regions, defined in this study as ⩽5.5 km from any road or ⩽1.0 km from navigable rivers, cover 35% of the region and incorporate 94.9% of all cleared forests.

Table 2
Land cover allocation within the accessible region in km^2. "Other" land cover classes include water and naturally occurring non-forest areas. Italics indicate allocation within separate protected area types that total to overall protected lands.

	Forest	Deforestation	Other	Total
Unprotected lands	554,589	428,597	146,742	1,129,928
Protected lands	196,845	24,026	48,453	269,324
Federal Strict Protection	*26,968*	*1152*	*5474*	*33,594*
State Strict Protection	*4935*	*765*	*963*	*6663*
Indigenous Reserves	*79,409*	*6137*	*23,725*	*109,270*
Federal Sustainable Use	*41,941*	*3841*	*1911*	*47,692*
State Sustainable Use	*43,593*	*12,131*	*16,381*	*72,104*
Totals	751,434	452,623	195,195	1,399,252

Protected land contained a higher percentage of remaining forest in all distance classes (Fig. 1). Protected areas showed resistance to deforestation, compared to unprotected forests, even when these forests were accessible; 10.9% of protected forests have been lost, compared with 43.6% of similarly accessible unprotected forests. Among the types of protection, Federal Strict Protection areas were the least impacted, with only 4.1% of accessible areas cleared. Both types of state-managed lands exhibited heavy impact, with 13.4% of strictly protected areas and 21.8% of sustainable use areas cleared.

Throughout the Brazilian Amazon, cleared forest area within PA boundaries totaled 32,381 km^2, with only 74.2% of clearing occurring in accessible regions. This suggests that smaller rivers, not included in our navigable river dataset, play a more important role in facilitating access to forests in PAs relative to the dynamics in unprotected forests. The 8355 km^2 of cleared protected forest outside the accessible area was mostly in indigenous reserves (40.1%) and sustainable use areas (47.8%) where small amounts of forest clearing are to be expected.

3.3. Effects of protected areas

The two scenarios for expected deforestation within PAs produced similar results (Table 3). The prevention scenario, where we assumed PA deforestation patterns with respect to roads to be similar to those observed in unprotected forests, produced an expected forest clearing of 61,792 km^2 within PAs. This is an increase of 177% (39,461 km^2) above observed clearing in PAs that could be considered to have been *avoided* because of protection. The displacement scenario, where the total observed deforested area in the accessible zone was held constant and simply redistributed evenly, regardless of protection status, produced an expected forest clearing of 56,831 km^2 within PAs. This represents an increase of 154% (34,500 km^2) over observed clearing that could be considered to have been *displaced* onto unprotected lands by the presence of protection. Sustainable use areas and indigenous reserves had the highest levels of expected deforestation, as they are by design accessible for extractive use and/or supporting local communities and are therefore most accessible by roadways and rivers. All protection types showed a mitigating effect on potential deforestation as driven by transportation networks, with Federal Strict Protection having the strongest effect (15–16% of expected deforestation) and State Sustainable Use the weakest (72–77% of expected deforestation). Despite comprising >40% of accessible protected area, indigenous lands only experienced 23–25% of the expected clearing under both scenarios.

The relationships between expected and observed deforestation over distance from roads for each scenario indicated common trends across all PA types (Fig. 3). Except for State Sustainable Use areas, all protection types experienced less than 50% of expected deforestation in close proximity to roads with increasing resilience to expected deforestation with distance in the first 2 km. Federal Sustainable Use areas demonstrated a decrease in this resilience towards the expected clearing at distances greater than the 2-km mark in both scenarios, but still remained below 50%. This may suggest that extractive practices such as floating timber out on rivers, or other clearing activities, are taking place in these sustainable use areas along waterways not included in our navigable rivers database. Although State Sustainable Use areas experienced a higher percentage of expected clearing than any other PA type, the amounts of deforestation were less than expected without protected status across all distances.

4. Discussion

Protected areas do not exist as isolated islands of pristine forest but are components within a larger matrix of human disturbance and activity (Chadzon et al., 2009; Laurance et al., 2012; Lovejoy, 2006). This surrounding matrix provides context to gauge the resilience of PAs in light of the development pressure they are under (Barber et al., 2012). Many PAs in the Amazon have been identified as having "default protection" due to their remoteness and inaccessibility (Adeney et al., 2009; Barber et al., 2012; Joppa et al., 2008). Here, we specifically examined protected lands under strong influence from an accepted primary driver of deforestation, proximity to transportation networks, to assess their resilience and the mitigating effects that different protection types are having on this risk.

Table 3
Allocation among the 5 protected area types of expected deforestation under two scenarios in km^2. The *prevention* scenario assumes that the presence of protection prevents deforestation that would otherwise occur while *displaced* assumes that expected clearing in protected areas is merely displaced into unprotected forests.

	"Prevention" expected clearing	"Displaced" expected clearing	Observed clearing	Prevented clearing	Displaced clearing
Federal Strict Protection	7360	6738	1084	6275	5653
Federal Sustainable Use	13,814	12,689	3570	10,244	9120
State Strict Protection	1908	1755	737	1171	1019
State Sustainable Use	16,439	15,316	11,826	4613	3491
Indigenous reserves	22,271	20,332	5114	17,157	15,218
Totals	61,792	56,830	22,331	39,460	34,501

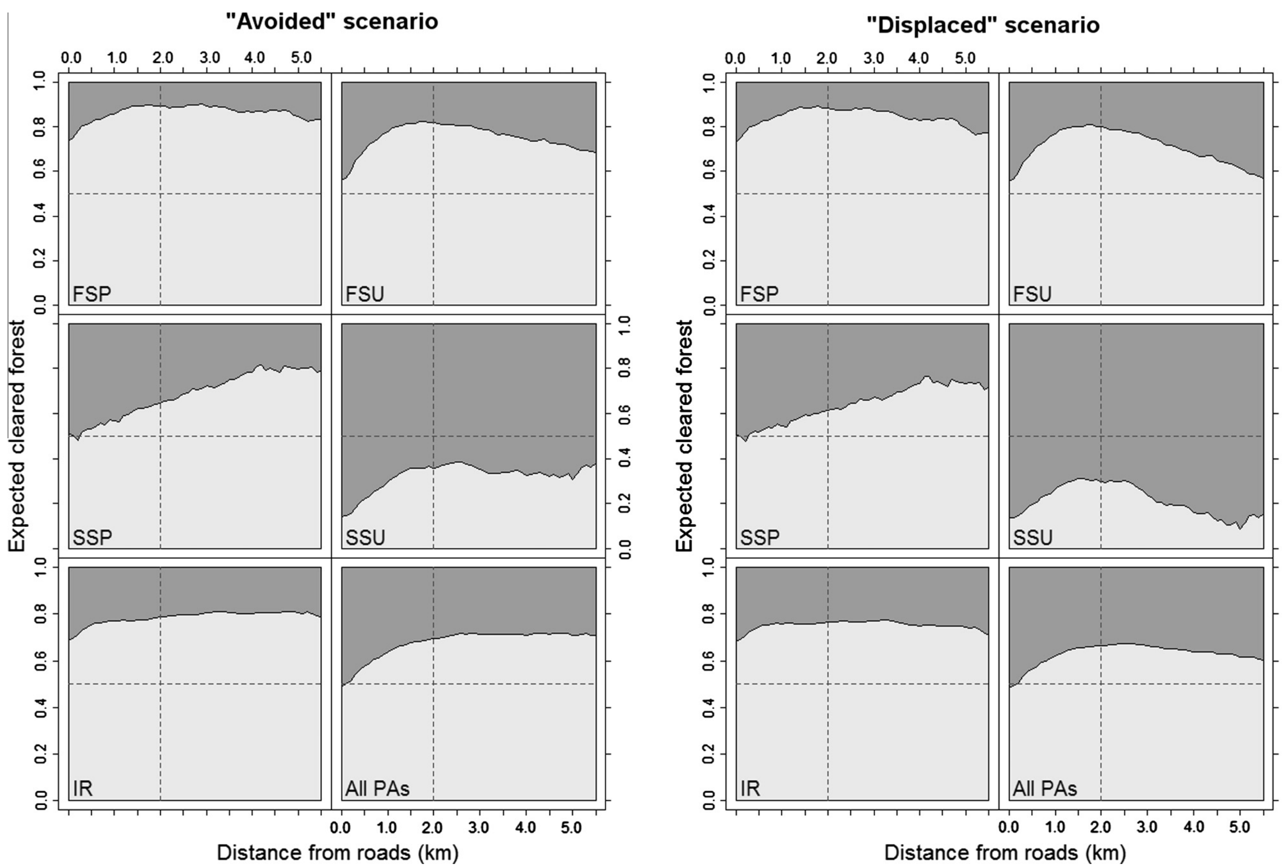

Fig. 3. Proportion of expected deforestation under both scenarios observed to be cleared as of 2006 (dark areas) and the proportion that remained as forest (light area) for each PA class and for all PAs combined. Hash marks indicate points discussed in text. (FSP: Federal Strict Protection, FSU: Federal Sustainable Use, SSP: State Strict Protection, SSU: State Sustainable Use, IR: Indigenous Reserves).

4.1. Role of unofficial roads and rivers

Large buffers based on the regional highway network are only roughly encapsulating the finer unofficial road network that extends from it, and by extension the forest loss attributable to that highway network. Distance from highways alone is too crude a metric to be useful since no meaningful accessibility is really offered at the large buffer distances needed to capture a majority of regional deforestation. Inclusion of all official and unofficial roads considerably shortens the distances defining 'accessible' forests to more physically plausible distances. Therefore, use of the comprehensive road network, vs. highways alone, vastly improves the spatial representation and attribution of the role that road access plays in deforestation. Conservation actions are implemented at local scales and the smaller distances of influence observed with the comprehensive road network is highly relevant to the practical implications of future conservation efforts as well as potential establishment of governance over the rapidly growing unofficial road network.

The addition of navigable rivers contributed little in terms of total area to the expectation of where deforestation would occur. This is consistent with past work that found that distance to navigable rivers was not a significant predictor of deforestation (Laurance et al., 2002). We chose to include this area in our assessment of accessible forest, however, as a large swath (75,000 km^2) of biologically important intact forest is within close proximity to a navigable river but inaccessible by roadways. Much of this forested area is protected – mostly in State Sustainable Use areas and Indigenous Reserves where transportation by river and some forest clearing is to be expected.

4.2. Within the accessible zone

We defined the accessible forest zone by combining the areas of strong influence from both the comprehensive road network and navigable rivers. This 1.4 million-km^2 area contains 94.9% of all Amazonian deforestation. A visual examination of deforestation outside this zone shows that most has occurred along presumed non-navigable rivers or within seasonally flooded forests greater than a kilometer from the mapped navigable channel. Additional small patches of isolated deforestation could be attributable to natural forest loss, such as blowdowns (Nelson et al. 1994), or to classification errors in the original PRODES land cover data. Unexplained linear deforestation features are likely attributable to narrow unofficial forest roads that were undetected in the satellite mapping and therefore not included in our unofficial roads database.

Within the accessible zone, nearly one-fifth of all lands have some protected conservation status. Comparable protected forests suffered only one quarter of the deforestation experienced by unprotected lands. Deforestation mitigation varied by protected status, with Federal lands being less prone to deforestation than State lands, and Strict Protection reducing deforestation more than Sustainable Use designation. State Sustainable Use areas had the most modest protection, with half as much deforestation as similarly accessible unprotected lands, while Federal Strict Protection regions had the greatest mitigation, reducing expected deforestation by over 80%.

Detailed comparison of forest clearing along 100-m distance classes from roadways showed a clear distinction in deforestation dynamics between protected and unprotected lands. Protected lands had both a lower percentage of total clearing and a stronger relationship between observed deforestation and road proximity than unprotected forest. This is consistent with but much more detailed than the findings of Adeney et al. (2009), who showed that protected and unprotected lands exhibited large differences in fire frequency within the first 10 km from roads and less difference beyond. We show the detailed spatial relationships between forest access and deforestation dynamics and how they vary as functions of management and protection status. Our results indicate that, while effective, protected areas are no panacea for deforestation in accessible forests. Careful planning and risk assessment must be conducted before implementing any new road construction within protected areas given the high deforestation risk inherent in these features. Limiting forest access is the primary deterrent to land clearing, but along transportation corridors, vigilant monitoring and enforcement of land use restrictions are critically important for mitigating deforestation activity.

4.3. Implications for REDD+

Our two scenarios for assessing the mitigating effects of protected areas represent two pure cases, one where deforestation is completely avoided and the other where it is displaced to unprotected land. The actual processes at work are likely a mix of both, and a mix that varies with location across the Brazilian Amazon. Although it is beyond the scope of this study, it is becoming increasingly important to disentangle the relative contributions of these two scenarios. Tropical deforestation contributes up to 25% of total anthropogenic greenhouse emissions (Houghton, 2005) and constitutes a driving force in global climate change. Global programs such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) have been proposed to mitigate these emissions. Protected areas can be strong, positive tools in REDD+ implementation if they can effectively reduce the total amount of forest clearing. However, if deforestation mitigation is only localized avoidance with the planned deforestation simply being displaced to another location further down the road, then REDD+ implementation is problematic, a process often referred to as "emission leakage" (Aukland et al., 2003; Henders and Ostwald, 2012).

Protected areas have been shown to slow the growth of road networks (Brandão and Souza, 2006), and we have shown here that they provide a mitigating effect toward the risk of outright forest clearing. However, the accessibility of some of these forests can increase the economic viability of extractive logging operations (Lentini et al., 2005; Souza et al., 2010) and lead to increased risk of illegal logging operations (Matricardi et al., 2007). While several studies have demonstrated the ability to detect forest loss due to logging operations (Asner et al., 2005; Souza et al. 2005, 2013), such losses are not included in the PRODES product used in this study. Road clearings contribute to forest fragmentation (Laurance et al., 2004) and an increased risk of fire (Cochrane, 2003). Additional activities such as extraction of non-timber forest products and hunting (Peres, 2000) also could have detrimental effects in these protected, yet accessible forests. Therefore, especially in the context of REDD+, a fuller accounting of the role of transportation network-facilitated access in promoting forest degradation is a necessary complement to this study of deforestation effects.

5. Conclusions

We find that 94.9% of all deforestation in the Brazilian Amazon has occurred in a well-defined accessible zone within 5.5 km of some type of roadway or 1.0 km of a navigable river. The overall effect of protected areas is clear: less than 1.5% of all protected forest throughout the region had been cleared by 2006. Protected forests experienced less forest loss than did unprotected lands at all distances from roads and navigable rivers. All protected area types mitigated deforestation risk and had four times less deforestation than unprotected areas even when highly accessible. The continued presence of protected areas is critical in the Amazon, and is especially crucial where forests are accessible via roads or navigable rivers.

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