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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 land-cover 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