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Effects of road infrastructure on forest value across a tri-national Amazonian frontier

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ABSTRACT

Road construction demonstrably accelerates deforestation rates in tropical forests, but its consequences for forest degradation remain less clear. We estimated a series of forest value metrics including components of biodiversity, carbon stocks, and timber and non-timber forest product resources, along the recently paved Inter-Oceanic Highway (IOH) integrating Brazil and Peru along the Bolivian border. We installed 69 vegetation plots in intact terra firme forests representative of local community holdings near and far from the IOH, and we characterized 15 components of forest value for each plot.

We observed strong geographic gradients in forest value components across the region, with increases from west to east in aboveground biomass and in the abundance of timber and non-timber forest product trees and regeneration. Plots in communities in Pando, Bolivia, where the IOH remains in part unpaved, had the highest aboveground biomass, standing timber volumes and Brazil nut tree density. In contrast, communities in Madre de Dios, Peru, where settlements and unpaved portions of the IOH have existed for decades, and in Acre, Brazil, where paving of the IOH has been underway for more than a decade, were more degraded. Seven of the fifteen forest value components we measured increased with increasing distance from the IOH, although the magnitude of these effects was weak. Landscape scale remote sensing analyses showed much stronger effects of road proximity on deforestation. We suggest that remote sensing techniques including canopy spectral signatures might be calibrated to characterize multiple components of forest value, so that we can estimate landscape scale impacts of infrastructure developments on both deforestation and forest degradation in tropical regions.

1. Introduction

The construction and paving of roads represent key factors responsible for tropical deforestation (Fearnside, 2005; Perz et al., 2007; Laurance et al., 2009; Ahmed et al., 2013). Beyond their physical footprint via conversion of forest to agricultural lands, pasture and settlements, roads also precipitate the degradation of remnant forests, in at least two ways. First, roads increase forest fragmentation (Forman et al., 2003; Fearnside, 2005), thereby creating edges with altered species composition due to novel environmental constraints and/or dispersal limitation (Benitez-Lopez et al., 2010). Second, roads provide access to areas that were previously isolated, which can lead to

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overexploitation of natural resources (Forman et al., 2003; Walker et al., 2013). Critically, these two types of effects can be synergistic, with edge effects being more pronounced in areas where the surrounding forest matrix has been modified by effects associated with roads such as fire or resource over-exploitation (Nepstad et al., 2001; Laurance et al., 2007). As a result, it remains imperative to assess the extent to which forest degradation due to roads can be mitigated by social–ecological factors such as governance by local communities (Perz et al., 2008; Pfaff et al., 2013) or national legislation (Barber et al., 2014; Laurance et al., 2014).

Although the distinction between deforestation and forest degradation has been recognized for some time, there remains debate regarding definitions of forest degradation (Sasaki and Putz, 2009; Asner et al., 2010). The most oft-employed approaches are based on forest cover estimates derived from remote sensing techniques (e.g., Hosonuma et al., 2012). However, forest cover may not be a valid proxy of forest value, or the tangible (e.g., timber) and intangible (e.g., water conservation) benefits conferred by particular forested areas (Ninan and Inoue, 2013; Baraloto et al., 2014). Forests with the same cover metric may differ substantially in structure and composition based on site factors such as climate and soil (Quesada et al., 2012), as well as the impacts of human disturbances such as logging and fire (Nepstad et al., 2001). Empirical field data therefore remain a necessary tool to provide precise estimates of both tangible and intangible components of forest value (Putz and Redford, 2008). Typically, studies examining road ecology have focused on biodiversity of specific taxa (Cousins, 2006; Benitez-Lopez et al., 2010; Hoskin and Goosem, 2010), even though mitigation of road impacts and forest degradation will require an integrative assessment of forest value combining multiple ecological attributes and ecosystem services (Freudenberger et al., 2013).

Debates about indicators of forest degradation in turn raise questions about whether roads affect different aspects of forests in the same way. Very clear general patterns have emerged regarding the effects of road proximity on forest cover, with for example 95% of deforestation events in the Brazilian Amazon found within 5 km of roads or 1 km of streams (Barber et al., 2014). However, contrasting predictions may emerge for the effects of road infrastructure on forest value. On the one hand, roads may accelerate forest degradation via increased resource harvesting (Nepstad et al., 2001; Perz et al., 2007). On the other hand, increased access to markets and alternative sources of livelihood may lessen the pressure on extant forest resources in some forest settlements (Perz et al., 2013a; Laurance et al., 2014).

Here we evaluate the impacts of a road infrastructure project on multiple metrics of forest value in forest communities of the tri-national frontier in the southwestern Amazon. The southwestern Amazon provides a useful study region in which to evaluate the impacts of road infrastructure on metrics of forest value. This region has significant forest diversity representing important biogeographic gradients from the Andes mountains to the lowland Amazonian forests (Phillips et al., 2006), including several economically important timber as well as non-timber forest product (NTFP) species. The region also contains a major road corridor, the Inter-Oceanic Highway (IOH), which was recently paved across the tri-national frontier of Bolivia, Brazil and Peru. Under the Initiative for the Integration of Regional Infrastructure in South America (IIRSA), the last unpaved segments of the IOH were paved in the southwestern Amazon from 2006 to 2010 to permit trans-boundary commerce between Brazil and Peru along the Bolivian border. The objective was to integrate the southwestern Amazon and other portions of the interior of South America into the global economy by providing export outlets via Atlantic ports in southern Brazil as well as Pacific ports in Peru (Perz et al., 2013a). Paving of the IOH has resulted in marked reductions in travel times to markets and urban centers for some of the remote communities (Perz et al., 2013a) and has been linked with reductions in forest cover of about 10% in the region, most of which has occurred within 20 km of the IOH (Southworth et al., 2011).

Communities in the region practice multiple use forest management, which includes harvesting of both timber, particularly cumaru (*Dipteryx* spp.), cumaru cetim (*Apuleia leiocarpa (Vogel) J. F. Macbr.*) and cedro (*Cedrela* spp.); and NTFPs including Brazil nuts (*Bertholletia excelsa Kunth.*), rubber (*Hevea brasiliensis (Willd. ex A. Juss.) Müll. Arg.*), sap resins and oils (*Copaifera* spp., *Myroxylon balsamum (L.) Harms*; *Hymenaea courbaril*) and palm fruits for food (*Euterpe precatoria Mart.*), in addition to subsistence hunting and materials consumption (Duchelle et al., 2011; Baraloto et al., 2014). There are incipient programs in place for environmental service payments related to carbon in the region, such as Acre's System of Incentives for Environmental Services, which was passed into state law in 2010 (Duchelle et al., 2013), along with multiple pilot REDD+ projects.

In this paper we evaluate the impacts of road infrastructure on forest value derived from empirical measures in forest vegetation plots. In particular, we respond to the following questions:

1) How do forest value components vary across the region with increasing distance from the foothills of the Andes?
2) How does proximity to roads, particularly the paved IOH, and to urban hubs of colonization affect forest value components across this gradient?
3) Are patterns of road effects consistent between the forest value estimates of this study and published deforestation metrics in the region (Southworth et al., 2011)?

2. Material and methods

2.1. Study sites

Sites were chosen to represent communities along the Inter-Oceanic Highway in Acre, Pando and Madre de Dios, Peru (MDD), as well as along the Cobija access road in Pando, Bolivia (Fig. 1). In each of the three border countries, 12–15 communities were selected for study to represent geographic variability and the major land tenure classes identified in the region, including agroextractive projects in Acre (Perz et al., 2013a). Broad variation in soils and climate in the region follows a general direction of the IOH along which we sampled, with the most fertile soils in the southwest and decreasing as one travels northeast into Acre (Phillips et al., 2003; Quesada et al., 2012). The three countries also contrast in (1) the paving status of the highway at the time of fieldwork, with Pando unpaved, MDD being paved, and Acre already paved; and 2) governance effort, with Acre having high governance of forests and MDD and Pando with weaker forest governance.

In each community, we worked with community leaders to identify forest sites that were representative of the area circumscribed by the community. Our objective was to focus on the average human impacts on the more common terra firme forests, so we avoided seasonally-inundated forests and areas that were not representative of the local landholdings because of extreme human impacts (or lack thereof). In most communities we chose one plot to be near (<2 km), and one plot to be farther (>5 km) from the IOH, with at least 5 km distance between any two plots. Some of the communities and sites that were identified for the study could not be included because inhabitants denied entry to inventory forest resources on their lands. Overall, we sampled 69 sites. A sensitivity analysis of statistical power indicated that this sampling was sufficient to detect hypothesized effects of the IOH on forest value components (Appendix S1).

2.2. Sampling methods

We sampled woody vegetation at each site between 2008 and 2010 using a modification of the Phillips et al. (2006) modified Gentry plot method (Baraloto et al., 2011), which has been demonstrated to be effective in measuring both aboveground biomass and floristic composition in Neotropical forests (Baraloto et al., 2013). Each woody plant rooted within the transect area and with a diameter at breast height (DBH at 1.3 m) of ≥2.5 cm was included and measured for both DBH