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## Anthropogenic drivers of headwater and riparian forest loss and degradation in a highly fragmented southern Amazonian landscape

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#### ABSTRACT

Freshwater ecosystems across the Amazon are largely comprised of small streams and headwaters of riparian zones. These areas are legally protected within private landholdings in Brazil, but recent changes in the environmental legislation have slackened protection requirements, with unpredictable consequences to the integrity and functioning of these freshwater environments. Local drivers of riparian forest loss and degradation should be understood by considering context-dependent land management practices and pressures within a region. Here, we examine the spatial determinants of the total amount and spectral quality of both headwater and overall riparian forests within private landholdings within a highly fragmented region of southern Amazonia. We built generalized linear models to assess how the amount and spectral quality of headwater and riparian forests respond to landholding size and distance to roads and an urban center, and document landholder compliance rates according to both the current and previous Brazilian environmental legislation. Although forest loss and degradation are typically associated, forest degradation responded independently to the same drivers. Headwater forests were generally more degraded than riparian forests, and smallholders complied less often with legal requirements than largeholders. Proximity to roads and the nearest town had a detrimental effect on both headwater and riparian forest amount and quality, and distance to the nearest town affected all variables. except for headwater forest quality. Compliance with environmental legislation is the first step in protecting riparian and headwater forests, but alternative landscape management strategies must be explored, particularly focusing on smallholdings, which are most vulnerable to deforestation and forest degradation.

#### 1. Introduction

The Amazon basin is the largest tropical forest system on Earth, encompassing the largest and most complex hydrographic network. Amazonian freshwater ecosystems cover over 1 million km<sup>2</sup>, drain  $\sim$  6.9 million km<sup>2</sup> of moist tropical forests, and discharge 20% of the world's surface freshwater into the Atlantic Ocean (Coe et al., 2008). Over two thirds of the entire freshwater system in the Amazon is estimated to consist of small stream riparian zones (Freeman et al., 2007), including thousands of headwater regions of small drainage basins. This represents a pivotal interface between aquatic and terrestrial ecosystems, where water, nutrients, and sediments are exchanged (Naiman et al., 2005). This hydrological system comprises an integral part of the Amazon basin, in that it provides key habitats for all aquatic and semiaquatic biodiversity, regulates climate and water flow at local and regional scales, and promotes sediment and nutrient transport and cycling, among other ecosystem services (Naiman and Decamps, 1997; Castello and Macedo, 2016).

Areas of Permanent Protection (hereafter, APPs) are legally required set-asides prescribed by the Brazilian Forest Code (Brasil 2012), and include both riparian and stream headwater zones in addition to other fragile landscape features. Their primary goal is to maintain hydrological functions, although their role in maintaining other ecosystem services, such as soil stabilization and landscape connectivity for both terrestrial and aquatic biodiversity are also explicitly recognized in the legislation. In the Amazon region, riparian and headwater zones comprise the most ubiquitous forms of APPs. Recent politically motivated changes in Brazilian environmental legislation, however, have greatly reduced the legal requirements for the restoration of native vegetation set-asides within private landholdings, and granted legal amnesty for most non-compliant landholdings that experienced high rates of illegal deforestation in the past, despite vigorous criticism from the scientific community (Lewinsohn, 2010; Metzger et al., 2010; Michalski et al., 2010b).

Most of the southern Brazilian Amazon has undergone severe deforestation since the late 1970s, creating an extensive fragmented

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landscape with varying degrees of forest cover (Michalski et al., 2008; Soler et al., 2009). This aging deforestation frontier was rapidly occupied by multiple waves of farmers in response to government-subsidized agrarian programs, and now largely consists of private landholdings of varying sizes. In contrast, state-managed protected areas are scarce (Michalski et al., 2010a), placing the fate of most forest ecosystems in the hands of private landowners. Most of the remaining natural vegetation cover throughout the tropics is now controlled by private and communal landholdings (Perfecto and Vandermeer, 2008; Gardner et al., 2009), and over half of all natural vegetation in Brazil currently persists within the ~5.5 million private landholdings (Ferreira et al., 2012). Deforestation in this region is largely driven by the economics of agricultural and livestock enterprises, but the relative contribution of different actors - namely small and large landholders depends on regional historical and socioeconomic contexts (Geist and Lambin, 2002; Michalski et al., 2010a; Arias, 2015). The discussion of how best to manage forest remnants or restore natural vegetation cover should therefore take into account context-dependent practices and pressures (Gardner et al., 2009). Understanding local imperatives of land stewardship that drive deforestation and forest degradation is critical in the discussion of how to counter-act the detrimental effects of policy changes, and should be done at the scale of individual properties, since this is the scale at which policy actions will ultimately be implemented (Aguiar et al., 2007; Gardner, 2013).

Tropical forest conservation science has largely focused on deforestation and fragmentation, whereas forest habitat degradation has been extensively overlooked (Ferreira et al., 2012). The Brazilian Forest Code (FC), which defines the minimum legal requirements for forest set-asides within private lands, is highly omissive concerning forest habitat quality. In this context, much work has focused on the contribution of small and large landholdings to forest loss (e.g. Aldrich et al., 2006; Aguiar et al., 2007; Michalski et al., 2010a; Gardner, 2013), while forest degradation has been widely neglected (Godar et al., 2014). Conservation actions planned under the UN/REDD+ (United Nations/Reducing Emissions from Deforestation and Forest Degradation) framework will require a high-resolution characterization of forest degradation patterns (Foley, 2007) and a more thorough mechanistic understanding of how both forest quality and forest amount are eroded over time (Gardner, 2012).

The goals of this study are therefore threefold. First, we describe the quantitative and qualitative patterns of riparian and stream headwater forests within APP areas in a highly fragmented region of southern Amazonia, at the scale of a ~900,000-ha municipal county. Second, we relate the amount of APP forests within 3366 variable-sized private landholdings to identify the potential consequences of legislative changes to the FC compared to previous legal requirements. Finally, we assess the environmental, geographic, and land-tenure determinants of property-scale patterns of riparian forest integrity, and how these drivers affect the spatial distribution of these patterns across the landscape. We hypothesized that both the amount and quality of riparian forests would be affected by (1) landholding size, because largeholders control larger economies of scale, and are therefore better able to comply with the legislation compared to smallholders; (2) distance to urban centres, which is a proxy of the intensity of urban pressure exerted on forest patches; and (3) distance to primary and secondary roads, which is likely related to both the age of deforestation and the economics of exploitation of forest remnants.

#### 2. Methods

#### 2.1. Study area

The Alta Floresta county, located in the northern Amazonian state of Mato Grosso (09°53'S, 56°28'W), encompasses a highly altered landscape spanning 894,605 ha, which has been severely deforested due to governmental incentives to establish bovine cattle farms in the region mainly during the 1980s and 1990s, following an ephemeral period of gold mining. Currently, a vast proportion of the county-scale landscape is comprised of cattle farms, forming a relatively homogenous matrix of low-quality exotic grass pastures in which forest fragments, riparian forests, and headwater forest patches of varying sizes and quality are embedded (Michalski et al., 2008). The Alta Floresta county contains a bovine herd size of 838,700 heads distributed across over 4000 landholdings of varying sizes. The county now represents one of the most altered regions of southern Amazonian forests, an area known in Brazil as the 'arc of deforestation'. Alta Floresta is therefore ideal to study the effects of severe deforestation and degradation patterns, as well pinpoint potential management alternatives that can inform other regions of Brazilian Amazonia.

#### 2.2. Landscape variables

The entire 894,605-ha study landscape was mapped using a supervised classification of 15-m resolution mosaic of RapidEye scenes, dated between July 2011 and August 2012. This classification was performed using the maximum-likelihood algorithm. We validated the resulting map using a  $\chi^2$  test of the confusion matrix using 243 independent ground-truthed GPS points (which were correctly classified more often than expected by chance:  $\chi^2 = 200.97$ ; p < .001). Overall accuracy obtained (number of correctly classified points/total number of validation points used) was 0.98. We were able to clearly distinguish five land-cover classes: (1) closed-canopy forest; (2) exotic grass pastures; (3) degraded and/or secondary forest; (4) low scrubby vegetation; and (5) and fast-growing tree (eucalyptus and teak) plantations. For the purposes of this analysis, we focused on the first three classes, because they were most prevalent across the landscape, and are associated with the process of large-scale deforestation and forest quality erosion, in which we were interested. Closed-canopy forest, cattle pastures and degraded/secondary forest comprised 46%, 45%, and 0.8% of the entire county area, respectively. Considering only riparian and headwater forest remnants, however, closed-canopy and secondary (or degraded) forest comprised 60% and 15% of the total area, respectively.

We obtained digital maps in vector format of the locations of all headwaters and streams/rivers across the study region from the Environmental Secretariat of Alta Floresta, following a detailed mapping assessment of the entire county, which were ground-truthed in situ (W. Butturi, pers. comm). The map was used to build a layer of 150-m buffer polygons (around points in the case of headwaters and lines in the case of streams), which we subsequently cross-referenced with our classified landscape map. These resulting maps were used to quantify the integrity status of forest patches, here defined as the total area of the three land-cover classes within the 150-m buffer around each headwater and riparian remnant (Fig. 1). The selection of this distance criterion allowed us to assess the degree to which remnant forest patches remained intact in a general context, since even past legal requirements sanctioned by the Brazilian FC are considered to be insufficient from an ecological perspective (Lima and Gascon, 1999; Lees and Peres, 2008; De Fraga et al., 2011; Bueno et al., 2012). In addition, a larger buffer area would have been less sensitive to small-scale coregistration errors and any spatial incongruence between the shapefiles describing remnant forest patches and hydrological features. Stream vector lines had their origin in the headwater point locations, so that riparian buffers included headwater buffers. Therefore, in our subsequent analysis, we tested overall riparian integrity against headwater integrity alone.

A map of all main and secondary roads, both paved and unpaved, throughout Alta Floresta was obtained from Instituto Centro de Vida (ICV), a non-governmental organization based in the county. We also obtained a map of 3366 private property polygons, which had been individually georeferenced across the entire county of Alta Floresta, from the Environmental Agency of Mato Grosso (SEMA), the municipal Download English Version:

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