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Tropical forest degradation and recovery in fragmented landscapes — Simulating changes in tree community, forest hydrology and carbon balance

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ABSTRACT

Empirical studies on severely fragmented regions suggest that decades after fragmentation, forest edges located near human-modified areas exhibit the structure of early successional states, with lower biomass per area and higher mortality compared to non-edge areas. These habitat changes (edge effects) can also have a considerable impact on ecosystem processes such as carbon and water balance, which in turn have a major impact on human activities.

Using field data from a long-term fragmented landscape in the Brazilian Northeastern Atlantic Forest, and the Forest Model FORMIND, we were able to visualize the time scale in which edge effects influence tropical forests by performing 500-year simulations. We observed changes in community composition, aboveground biomass, total evapotranspiration and total runoff.

Averages from ten four-hectare simulations show forest biomass degradation lasting around 100 years. If edge effects cease, recovery of biomass lasts around 150 years. Carbon loss is especially intense during the first five years after fragmentation, resulting in a decline of over 5 Mg $\text{ha}^{-1}\ \text{y}^{-1}$ C. Finally, edges of large fragments face an evapotranspiration loss of 43% and total runoff gains of 57% in relation to core areas of large fragments, suggesting that fragmented landscapes can be of significantly lower value in terms of ecosystem services.

1. Introduction

Land use leaves behind patches of natural areas which are often inaccessible due to the topography or the lack of road infrastructure (Angelsen and Kaimowitz, 1999; Laurance et al., 2002; Freitas et al., 2010). The vegetation remnants in these forest fragments typically go through several changes resulting in a community that differs from the original natural vegetation, before arriving in a new "relaxed state" (Diamond, 1972), or so-called dynamic equilibrium. This transition process drives the fragment to a different stable state in relation to its primary condition (Santos et al., 2008; Tabarelli and Lopes, 2008), which we will define here as "anthropogenic climax community" (ACC). This degradation process has also been called "retrogressive succession" (Tabarelli and Lopes, 2008). In a recently fragmented forest, many species are

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expected to go extinct. Thereafter, it takes a long time for original species abundance distributions to be restored and so ecological restoration activities are required if original levels are to be reached (Melo et al., 2013). The restoration of these forests, completing the cycle of the ''forest transition'' concept, also depends strongly on individual stakeholders and are frequently hindered when short-term economic benefits influence the decision making (Satake and Rudel, 2007).

Because human advances in tropical regions are fairly recent, most tropical forest fragments are not considered to have reached their final ACC. Loss of species and changes in their relative abundances occur at differing rates: fragments of up to 1000 ha experience half of their expected bird community extinctions in 50 years (Brooks et al., 1999), many of which are seed dispersers for numerous tree species (Silva and Tabarelli, 2000). A delay is thus expected between habitat changes and the number of future lost species (extinction debt), and this time interval has been estimated to be more than a century for trees in fragmented landscapes (Helm et al., 2006; Vellend et al., 2006). Since some species can have a disproportional effect on ecosystem function (Walker et al., 1999), we can also expect a delay in changes to measurements such as biomass, or processes such as evapotranspiration.

The degradation or retrogressive succession of the fragments has two main components. Besides being thrown into marked metacommunity dynamics, forest fragments exhibit striking changes in the vicinity of their borders, known as edge effects (Laurance, 1997). These effects are mainly driven by microclimatic changes which occur in forest edges, such as decreased humidity and increased light availability (Pinto et al., 2010). These microclimatic changes in turn cause a general increase in mortality in plant communities, as well as increased turnover and growth (Laurance et al., 2002). An empirical study lasting 32 years on forest edges in the Amazon has suggested that increased tree mortality in the first 100 m of forest fragment edges might be one of the most important processes driving the change of species abundance distributions and forest structure in forest fragments (Laurance et al., 2011). Other empirical studies have found that changes in species composition are related to their functional type, with late-successional, shade-tolerant species showing a decline in abundance at forest edges, and early-successional, shade-intolerant species showing increased abundance (Oliveira et al., 2008). Very large trees (emergent) are also especially vulnerable in small edge-effect dominated areas, and their loss contributes significantly to a reduction in average per hectare biomass values (Dantas de Paula et al., 2011). The spatial extent of edge effects has also been researched and debated: Although in the 32-year Amazon fragmentation experiment the main effects could be detected up to 100 m from the forest edge, in studies on long-term fragmented forests, edge effects on the tree community have been detected at up to 300 m in larger, preserved fragments, while in smaller ones (up to 300 m) the whole area could be considered to be in an edge state (Santos et al., 2008). Finally, understanding how much area in a landscape is affected by edge effects depends largely on the resolution used to map the forest area. Considering a 1000-m edge distance, using a 1 km^2 resolution satellite (AVHRR), in Africa 18%, in Asia 48%, in Australia 30% and in South America 14% of forests are affected by edge effects (Wade et al., 2003). This scale of analysis leaves out smaller fragments, which can compose a large part of a landscape's forests. Based on 30-m resolution LANDSAT data, a fragment size of at least 5 ha, and an edge distance of 300 m, 92% of fragments in the Brazilian Atlantic Forest were found to be affected by edge conditions (Dantas de Paula et al., 2011).

The shift in tree community and structure caused by edge effects can have a significant effect on the ecosystem processes occurring in forest fragments. One study on Amazonian forest fragments (Laurance, 1997) identified a significant loss of 36% biomass up to 100 m from the forest edge in 17-year-old forest fragments. In the Brazilian Northeastern Atlantic Forest (BNAF) with 200-year-old fragments, however, a loss of up to 60% biomass was found (Dantas de Paula et al., 2011). This loss produces carbon emissions amounting to 0.2 Pg C y-1 or 9%–24% of the annual global C loss due to deforestation, but are still not considered in global carbon accounting (Pütz et al., 2014). Another disruption caused by edge effects in forest fragments happens in forest hydrology. Trees pump soil water and return it to the atmosphere through transpiration, allowing 25%–56% of rainfall to be recycled within the ecosystem (Aragão, 2012). On the local scale, cleared forest areas have been known to present larger precipitation values than forested areas, but this has been demonstrated to be caused by a convectional process, which due to warmer conditions in the clearings, draws cool humid air from forests and sends it to the atmosphere, causing localized thunderstorms (Laurance et al., 2011). This process also causes further drier conditions at distances of up to 1.0–2.7 km from the forest edge, which exacerbate edge effects and increase the forest's vulnerability to fire (Cochrane and Laurance, 2008). On the regional scale, however, precipitation is reduced, as demonstrated by a study (Spracklen et al., 2012) which used satellite data to analyze the rain pattern of air masses that travel over forested regions. They found that for each leaf area index (LAI) increase of 1, there is an increase of 0.3–0.4 mm of daily rainfall. Air masses traveling over sparsely vegetated surfaces, however, lose moisture during continental transport because of reduced water recycling. Water also exits forests through surface runoff into streams and rivers. Preserved forests typically have less surface runoff than cleared areas because rainwater is better able to infiltrate the soil there, and takes much longer to saturate (van Dijk and Keenan, 2007). Therefore streams in fragmented landscapes experience greater temporal variation in flow, being exposed to more flooding events in the wet season, flow failure in the dry season, as well as increased sediment input (Nessimian et al., 2008; Trancoso et al., 2010). Understanding impacts of land-use changes on the hydrology of forests is vital for areas such as the BNAF, which is considered as a climate change hotspot and can be expected to experience water-related socio-climatic impacts in the future (de Sherbinin, 2013).

Although much attention is given to the degradation process of primary forests in fragmented landscapes, forests trapped in an ACC can recover and go back to dynamic states similar to the original condition (Laurance et al., 2011; Melo et al., 2013). The recovery process has been considered to be relatively fast (taking a decade or two) if protected from external disturbances, and a secondary forest will soon emerge surrounding a forest fragment, minimizing edge effects, and bringing