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Soil carbon stock changes due to edge effects in central Amazon forest fragments

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ABSTRACT

Amazon forest stocks large quantities of carbon both in plant biomass and in soil. Deforestation has accelerated the process of forest fragmentation in the Brazilian Amazon, resulting in changes in carbon stocks in both biomass and soil. Logging, including that under legal forest management, can create edge-like conditions inside the forest. We investigated the relationship between changes in carbon stocks in the soil and the distance to the nearest edge in forest remnants after about 30 years of isolation. We assessed the effect of edges using geographically weighted regression (GWR), which considers the non-stationary character of soil carbon stocks and assigns relative weights to the observations according to the distance between them. Data from 265 georeferenced plots distributed over 28 ha of forest fragments in the Manaus region were included in these analyses. Soil-carbon stocks were estimated for areas before (1984–1986) and after (2012–2013) isolation of the fragments. The GWR model indicated an apparent relationship between change in carbon stocks and distance from the edge ($R^2 = 0.79$). The largest changes occurred in plots located closest to the edges. In 202 plots $\leqslant$100 m from an edge, soil-carbon stock increased significantly ($p = 0.01$) by a mean of 1.34 Mg ha^{-1} over the ~30-year period. Such changes in soil carbon stocks appear to be associated with higher rates of tree mortality caused by microclimatic changes in these areas. Increased necromass inputs combined with changes in composition and structure of vegetation may result in increased rates of decomposition of organic matter, transferring carbon to the soil compartment and increasing soil carbon stocks. Considering both "hard" edges adjacent to deforestation and "soft" edges in logging areas, the soil-carbon increase we measured implies an absorption of 6×10^6 MgC in Brazilian Amazonia. In hard edges maintained for ~30 years, the soil-carbon increase offsets 8.3% of the carbon losses from "biomass collapse" in the first 100 m from a clearing. Soil carbon did not change significantly in 63 forest-interior plots, suggesting that global climate change has not yet had a detectible effect on this forest carbon compartment.

1. Introduction

The Amazon forest stocks large quantities of carbon in plant biomass (Nogueira et al., 2008, 2015; Saatchi et al., 2011) and in soil (Batjes, 2005; Batjes and Dijkshoorn, 1999; Fearnside, 2016; Fearnside and Barbosa, 1998). In the context of global warming these forests can play a strategic role in climate regulation (Fearnside, 1997). However, cumulative deforestation by 2015 (Brazil INPE, 2015) had destroyed 19.5% of Brazil's Amazonian forests. Annual deforestation rates declined from 2004 to 2012 and fluctuated around the 2012 level through July 2014. However, 2015 was marked by a rise in deforestation (Fearnside, 2015; Fonseca et al., 2015).

As a result of this process, continuous native forest cover has been replaced by a landscape dominated by isolated forest remnants in a matrix of farmland and pasture (Laurance and Bierregaard, 1997; Murcia, 1995; Saunders et al., 1991). The edge effect caused by fragmentation leads to increased tree mortality (Laurance et al., 1998) probably as a result of higher temperatures and decreased soil moisture at the forest edges compared to the forest interior (Camargo and Kapos, 1995), greater exposure to harsh winds (Rankin-de-Merona and Hutchings, 2001) and increased liana biomass at the forest edges (Laurance et al., 2014a,b).

Logging can produce edge-like conditions inside the forest because canopy gaps create a hotter and dryer microclimate and because inputs of necromass are increased from logging slash

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and logging-induced mortality (e.g., Asner et al., 2006; Broadbent et al., 2008). Canopy gaps and consequent microclimate alteration persist for 4–6 years after harvest (e.g., Gerwing, 2002), but frequent intrusion of fire and other disturbances means that many logged areas in Amazonia enter a cycle of continued degradation (e.g., Berenguer et al., 2014). Reduced impact logging (RIL) can reduce damage (Sist and Ferreira, 2007), and RIL normally has less canopy opening than the "conventional" logging that continues to be a common practice in Brazilian Amazonia (depending on the state, 46–65% of logged area is unlicensed: Monteiro et al., 2013; Silgueiro et al., 2015; a significant part of what is licensed is non-compliant with management requirements: e.g., Britto, 2015). Even RIL can result in up to 25% canopy opening (Jackson et al., 2002). Higher necromass inputs persist for over a decade even when increased mortality ceases shortly after the initial harvest (Blanc et al., 2009; Palace et al., 2007).

Economic activities in Amazonia that entail deforestation and forest degradation contribute substantial amounts of net emissions of greenhouse gases (Fearnside, 2000a). Estimates of emissions from conversion of forests into pastures do not explicitly consider soil-carbon stock changes in forest edges (Fearnside and Barbosa, 1998; Fearnside et al., 2009).

Deforestation in Brazilian Amazonia creates a landscape that is a mosaic of forest fragments embedded in a matrix of other land uses (mainly cattle pasture). The edges of these fragments lose substantial amounts of carbon from "biomass collapse" (Laurance et al., 1997). This carbon loss increases the impact of deforestation on global warming beyond the impact of carbon emission from the deforested areas themselves. However, the additional emission from edge formation only applies to the increase in the total length of edges in the region each year, not to the carbon loss from the much larger extent of edges present in the region that remains in place from each year to the next (Fearnside, 2000b). This is because the great majority of deforestation in Amazonia occurs by expansion of existing clearings into the surrounding forest, rather than by appearance of new clearings away from previously cleared areas. When existing clearings expand into adjacent forest, the forest edges are being cleared and the carbon stock in these areas has therefore already been reduced by the "biomass collapse" phenomenon. Counting the emission of deforestation based on the biomass of intact forest therefore would double-count the same carbon if the biomass-collapse emission has also been counted. The same reasoning that applies to biomass carbon stock changes also applies to soil carbon stock changes. Where Amazon forest is converted to cattle pasture (the predominant land use in deforested areas), soil carbon is lost under the normal system of pasture management (Fearnside and Barbosa, 1998).

The contribution of forest fragmentation to the balance of greenhouse-gas emissions is still poorly known. Most studies have focused on the evaluation of effects on plant biomass (Nascimento and Laurance, 2004, 2006) and litter (Didham, 1998; Sizer et al., 2000; Vasconcelos and Laurance, 2005; Vasconcelos and Luizão, 2004). Long-term effects of forest fragmentation on the stock of soil carbon remain unknown.

Amazonian soils store approximately 276 Mg of carbon per hectare at a depth of 0–8 m (Fearnside, 2016). Changes in forest structure that influence microclimate will affect the production and decomposition of organic matter, resulting in losses or gains of carbon stocks. The present study aims to assess changes in soil-carbon stocks due to edge effects in forest fragments that have been isolated for nearly 30 years.

2. Materials and methods

2.1. Study area

Our study was conducted on an experimentally fragmented landscape maintained by the Biological Dynamics of Forest Fragments Project (BDFFP). This project emerged during the discussions on the planning of protected areas known by the acronym "SLOSS" (Single Large Or Several Small reserves of equal area), which sought to assess the importance of the size of reserves for species conservation (Laurance et al., 2011). Forest fragments of different sizes (1, 10 and 100 ha) were isolated in three large cattle ranches for deployment of large-scale experiments in the early 1980s. The BDFFP's main objective was to establish the basis for assessments of the environmental consequences of deforestation and fragmentation on the Amazon rainforest. Isolated reserves were surrounded by cattle pastures.

Our study area is a 1000-km^2 experimental landscape that includes primary rainforest, forest fragments, and a matrix of cattle

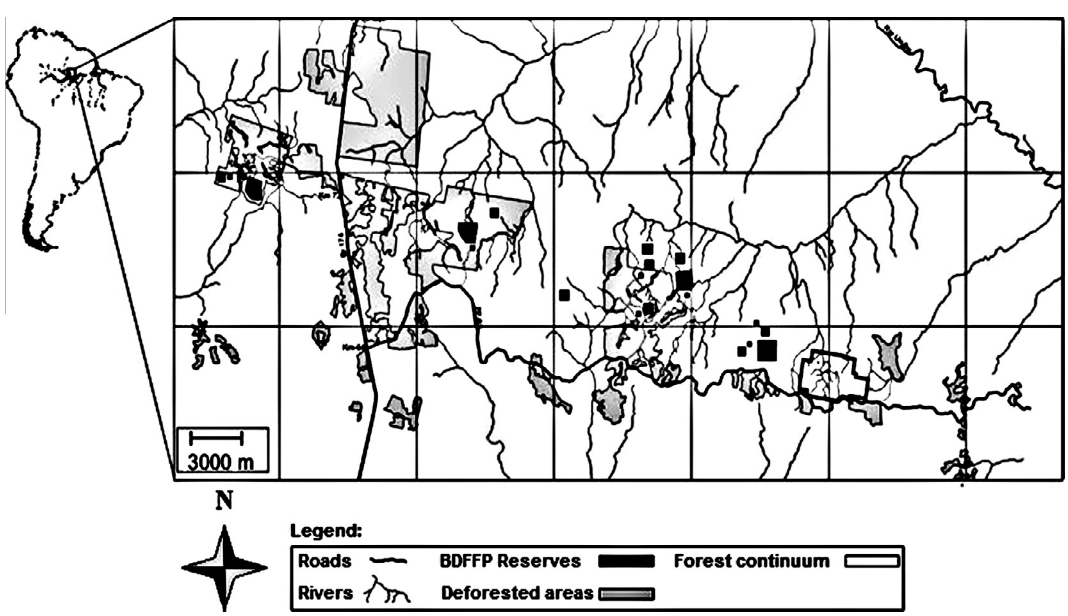

Fig. 1. Biological Dynamics of Forest Fragments Project (BDFFP).