Forest Ecology and Management 376 (2016) 74–83

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Soil types influence predictions of soil carbon stock recovery in tropical secondary forests

Claudia Pandolfo Paz [a,b,*], Miriam Goosem [a,b], Michael Bird [a,b], Noel Preece [b,c], Steve Goosem [b,d], Rod Fensham [e,f], Susan Laurance [a,b]

[a] College of Marine and Environmental Sciences, James Cook University, PO Box 6811, Building E1, Room 102K, Cairns, Qld 4870, Australia
[b] Centre for Tropical Environmental and Sustainability Science (TESS), Australia
[c] Biome5 Pty Ltd, PO Box 1200, Atherton, Qld 4883, Australia
[d] Wet Tropics Management Authority, Cairns, Qld 4870, Australia
[e] School of Biological Sciences, University of Queensland, Brisbane, Qld 4072, Australia
[f] Queensland Herbarium, Brisbane, Qld 4066, Australia

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form 1 June 2016
Accepted 3 June 2016
Available online 11 June 2016

Keywords:
Soil organic carbon (SOC)
Regrowth forests
Abandoned pastures
Wet Tropics
Australia

ABSTRACT

Tropical forests are major sinks of terrestrial carbon (C) both above- and below-ground. As a consequence their destruction and degradation is considered the second largest anthropogenic source of carbon dioxide to the atmosphere. Also contributing to the changing dynamics of the global carbon cycle is the widespread and significant expansion of secondary forest. Secondary forests that colonise abandoned agricultural lands can potentially recover above-ground C stocks to historical levels in a few decades. However, the dynamics of below-ground C stored as soil C stocks are unaccounted for in several tropical regions. Similarly, although parent materials are known to differ in chemical and physical properties, little is known about the relationships of soil C stocks with environmental predictors and whether they interact with soil types during natural forest regeneration. We investigated whether soil organic carbon (SOC) stocks change with secondary forest age in two contrasting soil types (derived from either basalt or granite). Soil and vegetation parameters were analysed to determine the best predictors of SOC stock changes in secondary forests. SOC stocks from 24 secondary forests (up to 69 years since pasture abandonment) were compared with those from active pastures and mature forests. We found that clay-rich soils (originating from basalt parent material) store higher amounts of SOC, although these stocks remain unchanged as secondary forests matured. In contrast, SOC stocks in granite soils tend to be lower in young secondary forests and increase rapidly to levels comparable to mature forests. Moreover, our analysis indicated that soil pH and woody plant diversity are strong candidates as predictors of SOC stock variations, yet it appears this is within the context of soil type. Our results support the contention that models predicting SOC stocks during forest succession should not rely only on secondary forest age. Instead, predictions of SOC stocks can be improved with the inclusion of basic information on vegetation cover and soil type (especially soil texture).

1. Introduction

Forests are a major carbon (C) sink (Dixon et al., 1994; Lal, 2005; Pan et al., 2011). Tropical mature forests contain *ca.* 471 ± 93 Pg C (above and below-ground biomass, dead wood, litter and soil) which represents 55 percent of the estimated C stock for all forest ecosystems (i.e. boreal, temperate and tropical forests; Pan et al., 2011). The first metre of tropical forest soil is of great importance in carbon stocks, contributing more than half of the total forest C (excluding roots) in Neotropical forests (Kauffman et al., 2009).

When tropical forests are cleared, substantial amounts of C are lost to the atmosphere (Fearnside and Barbosa, 1998; Pan et al., 2011). One of the main drivers of deforestation is agricultural expansion (Geist and Lambin, 2002). However, once soil productivity declines due to agricultural use, cleared lands are often abandoned and secondary forests subsequently colonise (Barbier, 1997; Munroe et al., 2013). This cycle of deforestation and

* Corresponding author at: College of Marine and Environmental Sciences, James Cook University, PO Box 6811, Building E1, Room 102K, Cairns, Qld 4870, Australia.
E-mail addresses: claudiappaz@gmail.com (C.P. Paz), miriam.goosem1@jcu.edu.au (M. Goosem), michael.bird@jcu.edu.au (M. Bird), noel@biome5.com.au (N. Preece), steve.goosem@wtma.qld.gov.au (S. Goosem), rod.fensham@dsitia.qld.gov.au (R. Fensham), susan.laurance@jcu.edu.au (S. Laurance).

http://dx.doi.org/10.1016/j.foreco.2016.06.007
0378-1127/

abandonment is contributing to the predominance of secondary forests over primary forest in the tropics today (ITTO, 2002; Chazdon, 2014). Therefore, secondary forests (considered here as the regrowth vegetation after land abandonment) have a crucial role in the global C budget (Lugo and Brown, 1992; Knops and Tilman, 2000; Letcher and Chazdon, 2009).

Despite a growing understanding of the factors that affect vegetation recovery and net productivity during forest succession there are uncertainties regarding the accumulation of soil organic C (SOC) (Buschbacher et al., 1988; Marín-Spiotta and Sharma, 2013). While above-ground biomass may recover rapidly after land abandonment (i.e. within a few decades); community structure and composition may continue to be dissimilar from the original forest even after many decades (Aide et al., 2000; Letcher and Chazdon, 2009; Goosem et al., 2016). Biomass accrual is expected to be a main determinant of SOC accumulation, however increase in SOC stocks after land abandonment appears to be variable and influenced by an array of factors (Guo and Gifford, 2002; Lal, 2005). For instance, alterations in the balance of soil nutrients and the characteristics of regenerating vegetation (e.g., species diversity and species composition) could be important determinants of SOC change over time (Davidson and Janssens, 2006).

Soil types vary in their fertility and can influence the distribution of plants and vegetation characteristics (Herrera and Finegan, 1997; Fyllas et al., 2009). Inherent properties of parent materials provide a range of physical and mineralogical features that affect the process of soil formation and vegetation recovery (FAO, 2005). However, with forest clearing and agricultural use, topsoils tend to become more compacted (i.e. less porous), which negatively affects oxygenation, water holding capacity, root penetration and soil biological communities (Kaiser and Guggenberger, 2003; Davidson and Janssens, 2006; von Lützow et al., 2007). Not surprisingly, therefore, soil types can respond differently in terms of soil C loss and accumulation after land-use transitions (Laganière et al., 2010; López-Ulloa et al., 2005; McLauchlan, 2006). Despite a growing interest, the influence of environmental parameters on SOC stock accumulation and their interaction with soil types during natural rainforest succession remains poorly documented in the tropics (Post and Kwon, 2000; Pan et al., 2011).

Our study region is comprised of a mosaic of active and abandoned pastures at various stages of natural succession (from *ca.* 9 to 69 years since pasture abandonment) and mature rainforest on different soil types. In this context, we were able to investigate SOC changes across a vegetation gradient on two contrasting parent material. We addressed two main questions. First, we asked whether soil types influence SOC stocks and dynamics (soil C isotopic composition) in active pastures, young (<30 years) and old (>30 years) secondary forests of different ages and mature forests. Secondly, we asked whether secondary forest age, soil properties, vegetation structure or woody plant community best predict SOC stock variation and whether these predictors are similar in both soil types.

SOC stock estimations should assist in placing tropical Australian secondary forests in a regional and global context, whereas the comparison of C isotopic composition should contribute to a better understanding of SOC dynamics during succession from pastures to older secondary forests (Trumbore et al., 1995; Schedlbauer and Kavanagh, 2008). Tracking changes in C isotopic signatures through secondary forest succession was possible because C_4 plant species (most commercial tropical species of pasture grass) comprise the dominant cover of active pastures in these warmer tropics. As forest succession proceeds, C_3 species are expected to outcompete pasture cover and dominate the site, gradually shifting the $\delta^{13}C$ signature back to forest levels (Peterson and Fry, 1987; Staddon, 2004; Schedlbauer and Kavanagh, 2008).

2. Methods

2.1. Study area

The study was carried out on the southern Atherton Tablelands in the Wet Tropics bioregion of Australia (17°25′32″S 45°36′13″E, Fig. 1). The study area is a 700–850 m plateau which experiences a mild tropical climate. Mean annual rainfall ranges from 1100 to 2240 mm and temperature ranges from a mean minimum of 10 °C in winter months to a mean maximum of 29 °C in summer months (BOM, 2014). Warmer and more humid weather occurs from December to March with a cooler and drier period from July to October, during which monthly rainfall falls below 100 mm. In the early 1900s, rainforest clearing began for the dairy industry, converting rainforest into pastures dominated by C_4 fodder grass species (Kerridge et al., 1972; Maggs and Hewett, 1993; Malcolm et al., 1999). Tropical C_4 grass species include *Paspalum* spp., *Imperata cylindrica* (L.) Raeusch. var. *major* (Ness) C. E. Hubb and *Axonopus affinis* Chase. There is no report of temperate or legume dominated pastures around our sites, although they have been recorded in southern regions (Malcolm et al., 1999). Pastures were abandoned due to changing financial incentives that led to a widespread decline in dairy farming. The pasture phase at our sites lasted from 40 to 100 years, which is considered sufficient time for changes in C isotopic signature in topsoil levels (Trumbore et al., 1995).

Soils in the study area are deep and highly weathered with relatively low concentrations of macro- and micro-nutrients (Kerridge et al., 1972; Malcolm et al., 1999). Basalt-derived soils dominate the Tablelands (56%), followed by granite-derived soils (23%), rhyolite (12%), metamorphic (7%) and Quaternary alluvial soil (2%). We selected sites on soils derived from the two dominant geological parent materials: granite (Tully Granite) and basalt (Atherton Basalt). Basaltic soils are classified as red and brown Ferrosols and normally contain higher proportions of clays and retain more organic matter, nutrients and water, whereas granitic soils are classified as red Dermosols, which comprise a sandier texture with lower organic matter content and high water infiltration rates (Kerridge et al., 1972; Malcolm et al., 1999).

2.2. Study sites

We surveyed 36 plots in total: twenty-four secondary forest stands (SF), six active pastures dominated by C_4 grasses (AP) and six mature forests as reference (MF). Study sites were chosen after examination of historical aerial photographs and satellite imagery, complemented by information from landowners. Active pastures were defined as man-made grasslands that are currently being grazed by cattle. Secondary forest was considered to be the vegetation regrowing spontaneously after pasture abandonment. Mature forest sites were old-growth rainforest sites that have not been cleared in the last 150 years, however, they might have been selectively-logged in the past century; as evidenced by logging tracks discernible on the ground and from aerial photography. We assume that these activities produced non-significant loss of SOC (Houghton, 1995). Active pastures and secondary forests were chosen so as not to be contiguous with the major rainforest tracts within the Wet Tropics World Heritage Area.

Secondary forest age was determined as the number of years since pasture abandonment. The age of secondary forest sites was determined as the mid-point year between two successive aerial photographs or satellite images where it was evident in the first that pasture had been abandoned and replaced by another vegetation type (e.g., low weeds, scramblers, shrubs and scattered tree saplings). We used secondary forest age as a continuous