Forest Ecology and Management 350 (2015) 40–45

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Silvicultural opportunities for increasing carbon stock in restoration of Atlantic forests in Brazil

Ana Paula C. Ferez [a], Otávio C. Campoe [b,*], João Carlos T. Mendes [c], José Luiz Stape [d]

[a] Instituto Centro de Vida, Cuiabá, MT 78043-055, Brazil
[b] Forestry Science and Research Institute – IPEF, Piracicaba, SP 13418-260, Brazil
[c] Departamento de Ciências Florestais, Universidade de São Paulo, USP-ESALQ, Piracicaba, SP 13418-260, Brazil
[d] Department Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695-8008, USA

ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form 9 April 2015
Accepted 10 April 2015
Available online 5 May 2015

Keywords:
Restoration plantation
Silviculture
Carbon stock
Atlantic forest

ABSTRACT

Deforestation for urbanization and agriculture expansion drastically reduced the area of the Atlantic forest biome in Brazil. To reverse this process, rehabilitating degraded lands, restoration plantations with native tree species show significant potential to rebuild the forest habitat and promoting carbon sequestration. High input silviculture (intensive fertilization and weed control), similar to those applied in commercial production forest plantations can increase productivity, accelerating forest restoration process. We evaluated the effects of two contrasting silvicultural systems, “traditional” (based on common silviculture of forest reforestation in Brazil – low input) and “intensive” (based on commercial plantations – high input) on carbon (C) stocks of a restoration plantation. We also compared the plantations with a mature forest remnant. Six years after planting, forest C stock (coarse roots and aboveground biomass) under intensive silviculture reached 23.3 Mg C ha^{-1}, more than 3-fold the stock under traditional silviculture (6.9 Mg C ha^{-1}). Under both silvicultural systems, soil showed constant C stock (average of 33 Mg C ha^{-1}). The C accumulation in biomass with intensive silviculture reached 12.8% of that stored in the mature forest (181.5 Mg C ha^{-1}), compared with just 3.8% for traditional silviculture. Intensive silviculture provided nutrients and reduced competition with weeds, increasing growth and carbon sequestration. Forest plantations aiming at restoration and also carbon sequestration are practicable, and are highly responsive to intensive silviculture.

1. Introduction

The Brazilian Atlantic Forest originally spanned from 4° to 32°S, with 1.2 million km^2 of evergreen forests, seasonally deciduous forests, and widely spaced gallery woodlands (Morellato and Haddad, 2000). The biome is considered a hot-spot for plant species richness and endemism, supporting over 20,000 species of vascular plants (Myers et al., 2000). Due to deforestation for urbanization and agriculture expansion, the biome has been reduced to less than 12% of its original cover, with remnant patches highly fragmented across the region (Ribeiro et al., 2009). To overcome this situation, forest restoration has a significant potential and has been successfully used (Chazdon, 2008; Ciccarese et al., 2012). Some methodologies of forest restoration use the natural resilience of the degraded ecosystem with minimum human interference in the process (Holl et al., 2003; Rodrigues et al., 2009). Others speed recovery by planting native tree species (Lamb et al., 2005). Forest restoration plantations on degraded areas can provide several benefits, such as soil and water conservation, biodiversity habitat and carbon sequestration (Benayas et al., 2009; Campoe et al., 2010; Kanowski and Catterall, 2010). Severely disturbed sites with depleted soils and no seed bank or nearby sources of seeds may benefit from the inputs of forest restoration plantations to catalyze forest regeneration (Parrotta et al., 1997).

Restoration plantations on degraded sites typically receive low-input silviculture, with little or no soil preparation, nutrient application and weed control. Weed control may be particularly important, as native tree species suffer severe competition from non-native invasive C4 grasses (Eyles et al., 2012). Intensive silvicultural systems that have been developed for monoculture plantations might also enhance forest restoration plantations (Gonçalves et al., 2008; Campoe et al., 2010).

Our objective was to compare the effect of two silvicultural systems (traditional with minimal inputs; and intensive with fertilization and weed control) on carbon stock and sequestration of a

---

* Corresponding author at: Forestry Science and Research Institute – IPEF, Via Comendador Pedro Morgante, 3500 Piracicaba, SP 13418-260, Brazil. Tel.: +55 19 2105 8694; fax: +55 2105 8666.

E-mail address: otavio@ipef.br (O.C. Campoe).

http://dx.doi.org/10.1016/j.foreco.2015.04.015
0378-1127/© 2015 Elsevier B.V. All rights reserved.

forest restoration plantation in degraded areas in Sao Paulo State, Brazil. We also compared the carbon stock of the planted forest ecosystem under both silvicultural systems with a typical mature Atlantic forest remnant as a representative reference of the regional biome. Our hypothesis is that intensive silviculture will increase carbon stock and sequestration of the forest plantation, compared to traditional, showing carbon stock closer to the Atlantic forest remnant amount.

2. Methods

2.1. Site description

The experiment was installed in riparian areas of Tiete River at Anhembi Forest Research Station, University of São Paulo (22°43′22″S, 48°10′32″W, 455 m of elevation, <2% slope). The native Atlantic Forests in this area were semi-deciduous seasonal forests (Morellato and Haddad, 2000). The climate is mesothermal Cwa (Alvares et al., 2013), with hot rainy summers and dry cool winters. The mean annual temperature is 23 °C and mean cumulated annual rainfall 1100 mm with annual water deficit of 20 mm during the dry season (May–August). The predominant soil is a deep acidic (pH of 4.0) Typic Hapludox (Soil Survey Staff, 1999), with 5% silt, 13% clay and 82% sand, with low organic matter (~1.5%, in the top 45 cm, Cook et al., 2013).

2.2. Experimental design

In March, 2004, 20 native tree species were planted on an abandoned and degraded pasture (Campoe et al., 2010). Before planting, the site was dominated by the African signal grass (*Urochloa decumbens*) which was eliminated by applying 5 L ha^{-1} of glyphosate (0.2%). Leaf-cutting ants (*Atta* sp. and *Acromyrmex* sp.) were controlled systematically with baits placed (sulfluramide 0.3%) throughout the experimental area.

The experimental design is a complete 2^3 factorial, with eight treatments in randomized blocks with four replications (32 plots of 36 m × 22 m each). The two levels of each factor were: (i) Proportion of pioneer and non-pioneer species: 50%:50% and 67%:33%; (ii) planting spacing: 3 m × 1 m (3333 plants ha^{-1}) and 3 m × 2 m (1667 plants ha^{-1}) and (iii) traditional and intensive silviculture (Campoe et al., 2010). Four additional plots (50%:50% pioneer and non-pioneer species, 3 m × 2 m, with intensive silviculture) were established to provide material for destructive sampling.

We focused our study on evaluating the effect of the factor silviculture, fixing the proportion of pioneers: non-pioneers in 50%:50%, and planting spacing of 3 m × 2 m. These proportion and spacing are widely used on restoration plantations on Atlantic forest biome. Thus, we evaluated only two treatments (traditional and intensive silviculture) in four replicates per treatment, totaling 8 plots monitored.

Traditional silviculture for the establishment of tree seedlings on abandoned pastures include hand row weeding (25 cm on each side) combined with mechanical mowing between rows (at 6, 12, 18 and 24 months after planting) and addition of moderate amounts of inorganic fertilizer, totaling 27 kg N ha^{-1}, 21 kg P ha^{-1}, 11 kg K ha^{-1} and 24 kg Ca ha^{-1} (Busato et al., 2007; Furtini Neto et al., 2004). The intensive silviculture was based on *Eucalyptus* plantations in Brazil (Stape et al., 2010; Gonçalves, 2013), providing total weed removal and high fertilization to alleviate any competition for water and nutrient limitation. Weed control was carried out chemically by the application of 5 L ha^{-1} of glyphosate (0.2%) across the entire plot, every three months until canopy closure and inhibition of weed growth (approximately 2 years after planting). After canopy closure, herbicide was spot applied as necessary, allowing natural regeneration. Fertilization was performed annually since planting time (March, 2004), totaling 81 kg N ha^{-1}, 62 kg P ha^{-1}, 33 kg K ha^{-1}, 452 kg Ca ha^{-1} and 180 kg Mg ha^{-1}.

2.3. Soil carbon stock

Total mineral soil carbon was determined from samples collected during experiment establishment and 6 years after planting. Soil bulk density was measured on samples collected using 100 cm^3 steel cylinders in the middle of each studied plot, at 0–15 cm and 15–30 cm soil depths, two between rows and two between plants in the row.

The soil C content was measured from samples collected with an auger, on two rows and two inter-rows at 0–15 cm and 15–30 cm. On each of these 4 locations, ten fixed positions were sampled and combined, totaling 4 samples per plot. Soil C contents were converted to an area basis by multiplying concentrations by average bulk density and sampling depth and summing the two depths. The C content on the top 30 cm of the soil profile represented 80% of the total C down to 45 cm depth, strongly decreasing below this depth (Cook et al., 2013).

2.4. Carbon stock

2.4.1. Tree measurements

Total height and bole diameter (0.3 m above ground level) were measured on all trees inside the measurable plot at 6 years after planting.

2.4.2. Biomass equations

Above and belowground biomass were estimated by allometric equations developed from destructive sampling. We selected 4 trees for each species comprising the range of sectional area, based on the inventory performed at 5 years after planting. The equations were developed by pooling all 80 trees (from 20 species) into a single group. On destructive additional plots, we identified the 80 selected trees, measured total height and diameter, harvested and divided the tree into the following components: Bole–stem and bark from ground level to the point of morphological change from bole to branch; branch–woody material after the point of morphological change between bole and branch until the diameter of 10 mm; crown–foliage and branches thinner than 10 mm; and coarse roots until the diameter of 10 mm. Each component of each tree, above and below ground, was weighed on site individually. Representative samples were collected and dried at 65 °C until constant weight for dry mass determination.

Based on the 80 harvested trees, we generated specific equations to three different components: (i) aboveground woody biomass (AGB_w) as a function of diameter, total height and wood density (see Ferez, 2012 for details on wood density determination); (ii) Coarse roots (CR) as a function of AWB; and (iii) crown biomass as a function of AWB and CR (Table 1). Bole sectional area of the sampled trees ranged from 3.8 cm^{-2} (*Cariniana estrellensisi*) to 432 cm^{-2} (*Erythrina mulungu*), total height from 1.30 m (*Cedrela fissilis*) to 10.55 m (*Jacaranda cuspidifolia*) and wood density from 220 kg m^{-3} (*Erythrina mulungu*) to 700 kg m^{-3} (*Acacia polyphylla*). The biomass equations were generated in R (R Development Core Team, 2008) using the linearized model of Schumacher and Hall (Chave et al., 2005). The data used to generate the equations passed on tests of normality and homoscedasticity of variance.

2.4.3. O horizon and herbaceous strata

The dry matter of the O horizon (litter layer above mineral soil) and herbaceous vegetation were quantified just before planting (degraded pasture) and 6 years after planting on all studied plots using a 0.5 m^2 (0.71 × 0.71 m) steel frame, on three positions on