

## Soil dynamics and carbon stocks 10 years after restoration of degraded land using Atlantic Forest tree species

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### Abstract

Brazil's Atlantic Forest ecosystem has been greatly affected by land use changes, with only 11.26% of its original vegetation cover remaining. Currently, Atlantic Forest restoration is receiving increasing attention because of its potential for carbon sequestration and the important role of soil carbon in the global carbon balance. Soil organic matter is also essential for physical, chemical and biological components of soil fertility and forest sustainability. This study evaluated the potential for soil recovery in contrasting restoration models using indigenous Atlantic Forest tree species ten years after their establishment. The study site is located in Botucatu municipality, São Paulo State-Brazil, in a loamy dystrophic Red-Yellow Argisol site (Typic Hapludult). Four treatments were compared: i) Control (Spontaneous Restoration); ii) Low Diversity (five fast-growing tree species established by direct seeding); iii) High Diversity (mixed plantings of 41 species established with seedlings) and; iv) Native Forest (well conserved neighboring forest fragment). The following soil properties were evaluated: (1) physical- texture, density and porosity; (2) chemical- C, N, P, S, K, Ca, Mg, Al and pH; (3) biological-microbial biomass. Litter nutrient concentrations (P, S, K, Ca and Mg) and C and N litter stocks were determined. Within ten years the litter C and N stocks of the Low Diversity treatment area were higher than Control and similar to those in both the High Diversity treatment and the Native Forest. Soil C stocks increased through time for both models and in the Control plots, but remained highest in the Native Forest. The methods of restoration were shown to have different effects on soil dynamics, mainly on chemical properties. These results show that, at least in the short-term, changes in soil properties are more rapid in a less complex system like the Low Diversity model than in the a High Species Diversity model. For both mixed plantation systems, carbon soil cycling can be reestablished, resulting in increases in carbon stocks in both soil and litter.

**Key words:** restoration models; recovery of degraded land; legume trees; physical properties; chemical properties; microbial biomass.

### Resumen

#### Dinámica del suelo y estoque de carbono después de diez años de la restauración de tierras degradadas usando especies arbóreas del Bosque Atlántico

El ecosistema forestal Atlántico de Brasil ha sido fuertemente afectado por los cambios en el uso de la tierra, restando solo 11,26% de su vegetación original. En la actualidad, la restauración forestal atlántica ha recibido creciente atención debido a su potencial para el secuestro de carbono y el importante papel del carbono del suelo en el equilibrio global del carbono. La materia orgánica del suelo es también esencial para el desarrollo físico, químico y biológico de la fertilidad del suelo y la sustentabilidad de los bosques. Este estudio evaluó el potencial de recuperación del suelo diez años después de su establecimiento en modelos contrastantes de restauración utilizando especies nativas de árboles forestales. El área de estudio esta localizada en el municipio de Botucatu, São Paulo-Brasil, en un suelo franco distrófica Argisol Rojo-Amarillo (Typic Hapludult) Fueron comparados cuatro tratamientos: i) Control (Restauración natural), ii) Baja diversidad (cinco especies de árboles de rápido crecimiento establecidos por siembra directa), iii) Alta diversidad (plantaciones mixtas de 41 especies establecidas con plántulas) y, iv) Bosque Nativo (fragmento de bosque vecino bien conservado). Las propiedades del suelo evaluadas fueron: (1) física-textura, densidad y porosidad, (2) química-C, N, P,

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S, K, Ca, Mg, Al y pH, (3) biológica-biomasa microbiana. Fueron determinadas también la concentración de nutrientes de hojarasca (P, S, K, Ca y Mg) y C, y el contenido de C y N del suelo. Después de diez años, la hojarasca y el contenido de C N del área de tratamiento de baja diversidad fueron más altos que el tratamiento control y similares a los de Alta Diversidad y Bosque Nativo. Las reservas de C del suelo incrementaron en el tiempo para ambos modelos y en las parcelas de control, pero siguen siendo más altas en el bosque nativo. Los métodos de restauración mostraron tener efectos diferentes sobre la dinámica del suelo, principalmente en las propiedades químicas. Estos resultados muestran que, en el corto plazo, los cambios en las propiedades del suelo son más rápidos en un sistema menos complejo como el modelo de baja diversidad que en el modelo de alta diversidad. Para ambos sistemas de plantación mixta, el ciclo del carbono del suelo puede ser restablecido, resultando en aumentos en el contenido de carbono en el suelo y la hojarasca.

**Palabras clave:** modelos de restauración; restauración de áreas degradadas; árboles leguminosas; propiedades físicas; propiedades químicas; biomasa microbiana.

## Introduction

The Brazilian Atlantic Forest, once covering approximately 139 million hectares, has been reduced to roughly 15.7 million ha, occurring in relatively small remnants of native vegetation (SOS Mata Atlântica and INPE, 2009; Ribeiro *et al.*, 2009). A large part of the deforested area has degraded soils, with changes in its physical, chemical and biological properties, resulting from misuse of land caused by anthropogenic activities or natural factors. Unsustainable land use, besides causing unbalance to the ecosystem, can influence the flow and stocks of carbon (LAL, 2005). Thus, the main scientific and technical challenges to mitigate the effects of degradation are to restore not only the structure but also the ecological functions of these ecosystems (Ewel, 1987; Young, 2000; Harris *et al.*, 2006; Engel and Parrotta, 2008).

Degradation implies a decrease in productive capacity and, in agriculture, is due mainly to erosive processes or mismanagement (Gonçalves *et al.*, 2008). The conversion of forests to agricultural crops affects many soil properties, but especially the concentration and storage of organic carbon in the soil. However, increased carbon storage in forest soils can be achieved through forest management practices, including soil preparation, fire management and associations of tree species. The sustainability of forestry plantations established on degraded sites depends on the recovery of soil fertility, essential for ecosystem restoration. Methods used to recover degraded soils should be based on technologies that involve not only the use of tree species that are both fast-growing as well as capable of restoring the soil by enhancing quality and quantity of soil organic matter.

One way to increase the content of organic matter in degraded soils is through the use of leguminous tree species. Numerous studies have focused on their capacity

and potential for soil fertility enhancement. For Macedo *et al.* (2008), the combined use of leguminous trees, nitrogen-fixing bacteria and arbuscular mycorrhizal fungi may be effective to restore nutrient cycling processes. In their study, decomposed litter was gradually incorporated into the soil, a technique that showed great potential to transform degraded lands into functioning ecosystems as carbon is absorbed by the soil. In highly degraded lands, McNamara *et al.* (2006) found that the use of *Acacia auriculiformis* supported the re-establishment of native species by eradicating competing grasses, and improving soil conditions, a process noted by other authors (c.f., Parrotta, 1992, 1999; Parrotta *et al.*, 1997; Carnus *et al.*, 2006; Bockerhoff *et al.*, 2008).

Among approaches to restore degraded ecosystems, there is a consensus that efforts will be only successful if they can yield a combination of economic, social and environmental benefits (Lamb *et al.*, 2005; Engel and Parrotta, 2008; Galatowitsch, 2009). The project «Atlantic Forest Restoration in Degraded Sites in the São Paulo State», initiated in 1997 in a 12-ha area on the campus of UNESP-Botucatu, aims to evaluate the potential ecological, economic and social benefits of different restoration models designed for application on small- and medium-sized farms. The general and specific results of this project can provide a better understanding of the restoration dynamics and contribute to development of standards for sustainable management of restored lands.

The present study was based on the assumption that during the process of restoration of degraded lands, the chemical and biological soil properties are gradually recovered while physical soil properties are preserved. We aimed at characterizing the changes in physical, chemical and biological soil properties resulting from the development of tree species introduced in two different restoration models in comparison to control sites and the native forest.

## Material and methods

The study site is located at the São Paulo State University (UNESP) at Botucatu (22° 50' S, 48° 24' W), at 574 m altitude in the central-southern region of São Paulo State, Brazil. The climate is classified as Cfa (Köppen). Between 1971 and 2009, the annual precipitation averaged 1494 mm, the wettest months occurring during the period from October to March; and the annual temperature averaged 20.5°C, with minimum and maximum average temperatures occurring in July and February, respectively. The natural vegetation is classified as semi-deciduous tropical forest within the Atlantic Forest region. The soil is an Ultisol (Red-Yellow Argisol; Oliveira, 1999), with undulated topography. From 1920 to 1971, the area was used for pasture. Afterwards, one part of the area was used for citrus crops and another for grassland, dominated by *Brachiaria decumbens*. After its establishment, the study site was fenced and protected against fire.

Four treatments were studied:

(1) *Control*: Experimental treatment with vegetation in process of natural regeneration, without intervention and management.

(2) *Low diversity*: Five early-successional tree species (*Chorisia speciosa*, *Croton floribundus*, *Enteolobium contortisiliquum*, *Mimosa scabrela* and *Schizolobium parahyba*), planted by direct seeding in March 1997, following seed treatments to break dormancy as indicated for each species. Seeds were planted at 1 × 1 m spacing at 5 cm depth, using 2-4 seeds per planting spot. The plots were prepared with a soil ripper (to 40 cm depth), and with preliminary herbicide application over the total area.

(3) *High diversity*: Conventional planting of seedlings, using a mixture of 41 native species from different ecological groups found in the semi-deciduous tropical forest of the region. Seedlings were produced in the nursery of the Natural Resources Department of UNESP. Site preparation included conventional tillage (plowing and disking) in November and December 1997, with planting carried out between January and February 1998.

(4) *Native forest*: A fragment of native forest in good condition located near experimental area, used as a reference ecosystem for soil properties and accumulated litter.

The Control, Low Diversity and High Diversity treatments were installed in a randomized block design with three replications. Three plots in each treatment

were assessed, each plot with an area of 2,500 m<sup>2</sup> (50 × 50 m). The Native Forest study plots were located near study site.

The texture, particle density and bulk density ( $\rho$ ) were determined according to the standard methods proposed by EMBRAPA (1997). The sampling was conducted in June 1998 and October 2007. For the assessment of texture and particle density, the soil was sampled at 0-10, 10-20 and 20-40 cm depth. Bulk density was sampled at 0-10 and 10-20 cm depth. Porosity was calculated by the following equation:

$$Y = [(\text{particle } \rho - \text{bulk } \rho) / \text{particle } \rho] * 100.$$

Soil fertility parameters were assessed using the methods described by Raij *et al.* (2001), considering the following characteristics: organic carbon, N, available P, S, K, exchangeable Ca, Mg and Al, and pH. Chemical properties were determined at 0-5, 5-10, 10-20 and 20-40 cm depth, in four periods: 1998, 1999, 2007 and 2010. The microbial biomass carbon was assessed at 0-5 and 5-20 cm, in July 1998, January 1999, October 2007 and March 2010, and analyzed using the method described by Vance *et al.* (1987).

For the analysis of texture, particle density, chemical properties and microbial biomass, composite samples consisting of 12 individual samples per plot, collected with an auger, were prepared. For analysis of bulk density, four undisturbed samples of 98 cm<sup>3</sup> per plot were collected in 5 × 5 cm cylinders. Different soil sampling depths were used for assessment of these parameters because of variation of these properties with depth, and to facilitate comparison of data with those of other studies.

Litter accumulation was assessed in November 2007, May and November 2008 and May 2009. In each assessment period, 12 circular samples per plot, each with diameter of 45 cm (166 cm<sup>2</sup>) were collected using a systematic sampling design. These twelve samples were combined for a composite plot sample of 2 m<sup>2</sup>. The litter of each composite sample was dried at 65°C for 72 h and weighed. These samples were analyzed for total C, N, P, S, K, Ca and Mg (EMBRAPA, 1997). The averages of the four periods were considered to estimate carbon and nitrogen stocks in the accumulated litter.

All data were subjected to analysis of variance (ANOVA or GLM) and treatments were compared using the Tukey test ( $P < 0.05$ ). The statistical program used for analysis was SAS (2009) version 9.2.

**Table 1.** Physical properties at different soil depths; mean values  $\pm$  standard error for the different treatments in October 2007 (10 years after experiment setup); for texture and particle density  $n = 3$  and for bulk density and porosity  $n = 12$ 

Depth and treatment	Texture			Density		Porosity (%)
	Clay (g kg <sup>-1</sup> )	Silt (g kg <sup>-1</sup> )	Sand (g kg <sup>-1</sup> )	Particle (g dm <sup>-3</sup> )	Bulk (g dm <sup>-3</sup> )	
<i>0-10 cm</i>						
Control	70 <sup>a</sup> $\pm$ 3.7	26 <sup>a</sup> $\pm$ 3.2	904 <sup>a</sup> $\pm$ 6.7	2.7 <sup>a</sup> $\pm$ 0.0	1.35 <sup>a</sup> $\pm$ 0.02	50 <sup>b</sup> $\pm$ 3
Low diversity	84 <sup>a</sup> $\pm$ 4.3	22 <sup>a</sup> $\pm$ 4.0	894 <sup>a</sup> $\pm$ 6.7	2.7 <sup>a</sup> $\pm$ 0.0	1.32 <sup>a</sup> $\pm$ 0.02	51 <sup>b</sup> $\pm$ 3
High diversity	77 <sup>a</sup> $\pm$ 6.9	20 <sup>a</sup> $\pm$ 4.7	903 <sup>a</sup> $\pm$ 2.3	2.7 <sup>a</sup> $\pm$ 0.1	1.41 <sup>a</sup> $\pm$ 0.04	48 <sup>b</sup> $\pm$ 4
Native forest	63 <sup>a</sup> $\pm$ 11	36 <sup>a</sup> $\pm$ 9.0	901 <sup>a</sup> $\pm$ 18	2.6 <sup>a</sup> $\pm$ 0.1	1.01 <sup>b</sup> $\pm$ 0.06	61 <sup>a</sup> $\pm$ 4
<i>10-20 cm</i>						
Control	69 <sup>ab</sup> $\pm$ 7.2	30 <sup>a</sup> $\pm$ 2.9	901 <sup>a</sup> $\pm$ 10	2.9 <sup>a</sup> $\pm$ 0.2	1.56 <sup>a</sup> $\pm$ 0.01	46 <sup>a</sup> $\pm$ 4
Low diversity	81 <sup>a</sup> $\pm$ 5.6	20 <sup>a</sup> $\pm$ 6.7	899 <sup>a</sup> $\pm$ 9.2	2.8 <sup>a</sup> $\pm$ 0.2	1.57 <sup>a</sup> $\pm$ 0.03	44 <sup>a</sup> $\pm$ 5
High diversity	74 <sup>a</sup> $\pm$ 10	25 <sup>a</sup> $\pm$ 10	901 <sup>a</sup> $\pm$ 3.3	2.7 <sup>a</sup> $\pm$ 0.1	1.54 <sup>a</sup> $\pm$ 0.02	43 <sup>a</sup> $\pm$ 4
Native fForest	42 <sup>b</sup> $\pm$ 1.2	26 <sup>a</sup> $\pm$ 3.8	932 <sup>a</sup> $\pm$ 5.0	2.7 <sup>a</sup> $\pm$ 0.0	1.38 <sup>b</sup> $\pm$ 0.02	49 <sup>a</sup> $\pm$ 3
<i>20-40 cm</i>						
Control	124 <sup>a</sup> $\pm$ 6.2	22 <sup>a</sup> $\pm$ 7.3	853 <sup>b</sup> $\pm$ 6.0	2.6 <sup>a</sup> $\pm$ 0.1	—	—
Low diversity	132 <sup>a</sup> $\pm$ 7.5	15 <sup>a</sup> $\pm$ 3.6	853 <sup>b</sup> $\pm$ 3.8	2.6 <sup>a</sup> $\pm$ 0.2	—	—
High diversity	127 <sup>a</sup> $\pm$ 8.7	19 <sup>a</sup> $\pm$ 4.6	854 <sup>b</sup> $\pm$ 2.4	2.6 <sup>a</sup> $\pm$ 0.1	—	—
Native forest	42 <sup>b</sup> $\pm$ 10	15 <sup>a</sup> $\pm$ 4.7	943 <sup>a</sup> $\pm$ 12	2.6 <sup>a</sup> $\pm$ 0.1	—	—

Means followed by the same letter in the same column in each soil depth are not significantly different (Tukey test,  $P < 0.05$ ).

## Results

For some soil physical properties and soil depths, the Native Forest (reference) differed from the Control, Low Diversity and High Diversity treatments, which did not differ significantly from one another (Table 1). Soil bulk density and porosity at 0-10 cm depth, clay content and bulk density at 10-20 cm and clay and sand contents at the 20-40 cm showed differences between

the Native Forest and the other treatments. The comparison of data from July 1998 with those from October 2007 allowed detection of changes of physical properties at 0-10 cm depth (Table 2). Soil layers at 10-20 and 20-40 cm also showed similar, though less marked, differences between treatments as those found at 0-10 cm. In all treatments, the bulk density decreased and therefore porosity increased. The Low Diversity treatment also showed a decrease in sand content.

**Table 2.** Physical properties at 0-10 cm soil depth in different treatments, respectively, 6 months and 10 years after experiment setup; mean values  $\pm$  standard error; for texture and particle density  $n = 3$ ; for bulk density and porosity  $n = 12$ 

Treatment	Period	Texture			Density		Porosity (%)
		Clay (g kg <sup>-1</sup> )	Silt (g kg <sup>-1</sup> )	Sand (g kg <sup>-1</sup> )	Particle (g dm <sup>-3</sup> )	Bulk (g dm <sup>-3</sup> )	
Control	Jun/98	87 <sup>a</sup> $\pm$ 7.0	20 <sup>a</sup> $\pm$ 0.0	893 <sup>a</sup> $\pm$ 6.7	2.6 <sup>a</sup> $\pm$ 0.1	1.47 <sup>a</sup> $\pm$ 0.07	42 <sup>b</sup> $\pm$ 2
	Oct/07	70 <sup>a</sup> $\pm$ 3.7	26 <sup>a</sup> $\pm$ 3.2	904 <sup>a</sup> $\pm$ 6.7	2.7 <sup>a</sup> $\pm$ 0.0	1.35 <sup>b</sup> $\pm$ 0.02	50 <sup>a</sup> $\pm$ 3
Low diversity	Jun/98	80 <sup>a</sup> $\pm$ 0.0	0 <sup>a</sup> $\pm$ 0.0	920 <sup>a</sup> $\pm$ 0.0	2.5 <sup>a</sup> $\pm$ 0.1	1.45 <sup>a</sup> $\pm$ 0.08	42 <sup>b</sup> $\pm$ 3
	Oct/07	84 <sup>a</sup> $\pm$ 4.3	22 <sup>a</sup> $\pm$ 4.0	894 <sup>b</sup> $\pm$ 6.7	2.7 <sup>a</sup> $\pm$ 0.0	1.32 <sup>b</sup> $\pm$ 0.02	51 <sup>a</sup> $\pm$ 3
High diversity	Jun/98	87 <sup>a</sup> $\pm$ 7.0	20 <sup>a</sup> $\pm$ 0.0	893 <sup>a</sup> $\pm$ 6.7	2.5 <sup>a</sup> $\pm$ 0.1	1.47 <sup>a</sup> $\pm$ 0.14	42 <sup>b</sup> $\pm$ 2
	Oct/07	77 <sup>a</sup> $\pm$ 6.9	20 <sup>a</sup> $\pm$ 4.7	903 <sup>a</sup> $\pm$ 2.3	2.7 <sup>a</sup> $\pm$ 0.0	1.41 <sup>a</sup> $\pm$ 0.04	48 <sup>a</sup> $\pm$ 4
Native forest	Jun/98	60 <sup>a</sup> $\pm$ 0.0	20 <sup>a</sup> $\pm$ 0.0	920 <sup>a</sup> $\pm$ 0.3	2.6 <sup>a</sup> $\pm$ 0.1	1.24 <sup>a</sup> $\pm$ 0.13	53 <sup>b</sup> $\pm$ 3
	Oct/07	63 <sup>a</sup> $\pm$ 11	36 <sup>a</sup> $\pm$ 9.0	901 <sup>a</sup> $\pm$ 18	2.6 <sup>a</sup> $\pm$ 0.0	1.01 <sup>b</sup> $\pm$ 0.06	61 <sup>a</sup> $\pm$ 4

Means followed by the same letters in columns in each treatment are not significantly different between periods (Tukey test,  $P < 0.05$ ).

The Control, Low Diversity and High Diversity treatments had values of some chemical properties below those of the Native Forest, demonstrating that they were still far from restoring the original fertility of the soil (Table 3). When comparing the Control, Low Diversity and High Diversity treatments, few differences were detected in terms of chemical properties, although the Low Diversity treatment that had the highest Al content at 0-5 cm soil depth. In this layer, from July 1998 to January 2010, several changes were observed for some soil chemical properties resulting from effects of the treatment over time (Table 4). In the deeper layers (5-10, 10-20 and 20-40 cm), changes followed the same pattern as in 0-5 cm soil depth. The organic matter content increased for the two restoration models and Control. The Low Diversity treatment had a significant reduction of the P content. The S content increased in the Native Forest and decreased in the Low Diversity treatment. The K content decreased in the Native Forest and was variable for the other treatments. The Mg content showed no significant differences

between the two sampling dates. The Low Diversity treatment and Control had increased Al content and reduced pH values.

The soil C stocks at 0-5 cm depth did not show differences among treatments (Table 5). The N stock was higher in Native Forest. Ten years after establishment of the experimental treatments, the soil C:N ratio in the Low Diversity and High Diversity treatments were similar to that of the Native Forest. For the C and N stocks in accumulated litter, the Low Diversity treatment differed from the Control and was similar to the Native Forest (Table 5). The C:N ratio of accumulated litter in the two restoration models differed from the Control, but was still higher than that found in the Native Forest. In terms of nutrients in accumulated litter, the High Diversity treatment showed higher contents of P and Ca than the Low Diversity and Control treatments and approached that of the Native Forest for Mg content (Table 6). The Low Diversity treatment was not different from the Control for all nutrients assessed, and was not significantly different than

**Table 3.** Chemical properties in different soil depths; mean values ( $n=3$ )  $\pm$  standard error for the different treatments in October 2007, 10 years after experiment setup

Depth and treatment	pH	P	S	K	Ca	Mg	Al
	CaCl <sub>2</sub>	Resine	SO <sub>4</sub> <sup>2-</sup>				
<i>0-5 cm</i>							
Control	4.9 <sup>a</sup> $\pm$ 0.1	15 <sup>a</sup> $\pm$ 2.6	6.0 <sup>b</sup> $\pm$ 0.5	3.0 <sup>ab</sup> $\pm$ 0.3	21 <sup>b</sup> $\pm$ 1.3	11 <sup>a</sup> $\pm$ 0.5	0.8 <sup>b</sup> $\pm$ 0.1
Low diversity	4.5 <sup>a</sup> $\pm$ 0.1	13 <sup>a</sup> $\pm$ 0.4	6.7 <sup>b</sup> $\pm$ 0.6	2.3 <sup>b</sup> $\pm$ 0.1	20 <sup>b</sup> $\pm$ 1.9	12 <sup>a</sup> $\pm$ 1.3	1.8 <sup>a</sup> $\pm$ 0.1
High diversity	5.2 <sup>a</sup> $\pm$ 0.2	13 <sup>a</sup> $\pm$ 4.0	6.0 <sup>b</sup> $\pm$ 0.7	3.0 <sup>ab</sup> $\pm$ 0.6	24 <sup>b</sup> $\pm$ 3.1	12 <sup>a</sup> $\pm$ 1.2	0.7 <sup>b</sup> $\pm$ 0.2
Native forest	5.7 <sup>a</sup> $\pm$ 0.6	22 <sup>a</sup> $\pm$ 0.8	22 <sup>a</sup> $\pm$ 2.1	4.4 <sup>a</sup> $\pm$ 0.5	89 <sup>a</sup> $\pm$ 15	14 <sup>a</sup> $\pm$ 1.3	0.4 <sup>b</sup> $\pm$ 0.3
<i>5-10 cm</i>							
Control	4.7 <sup>b</sup> $\pm$ 0.2	9.5 <sup>a</sup> $\pm$ 1.5	4.6 <sup>b</sup> $\pm$ 0.5	2.0 <sup>b</sup> $\pm$ 0.2	12 <sup>b</sup> $\pm$ 0.0	6.8 <sup>b</sup> $\pm$ 0.6	1.7 <sup>ab</sup> $\pm$ 0.5
Low diversity	4.3 <sup>b</sup> $\pm$ 0.1	9.2 <sup>a</sup> $\pm$ 0.8	5.8 <sup>b</sup> $\pm$ 0.4	1.8 <sup>b</sup> $\pm$ 0.1	10 <sup>b</sup> $\pm$ 2.0	7.8 <sup>ab</sup> $\pm$ 0.7	3.7 <sup>a</sup> $\pm$ 0.9
High diversity	4.6 <sup>b</sup> $\pm$ 0.1	8.9 <sup>a</sup> $\pm$ 1.9	5.3 <sup>b</sup> $\pm$ 0.3	2.0 <sup>b</sup> $\pm$ 0.3	13 <sup>b</sup> $\pm$ 1.6	7.5 <sup>ab</sup> $\pm$ 0.6	2.1 <sup>ab</sup> $\pm$ 0.7
Native forest	5.8 <sup>a</sup> $\pm$ 0.4	13 <sup>a</sup> $\pm$ 1.2	13 <sup>a</sup> $\pm$ 1.2	3.4 <sup>a</sup> $\pm$ 0.2	50 <sup>a</sup> $\pm$ 6.8	10 <sup>a</sup> $\pm$ 0.7	0.4 <sup>b</sup> $\pm$ 0.2
<i>10-20 cm</i>							
Control	4.5 <sup>b</sup> $\pm$ 0.2	5.4 <sup>b</sup> $\pm$ 0.3	5.0 <sup>b</sup> $\pm$ 0.4	1.3 <sup>b</sup> $\pm$ 0.1	11 <sup>b</sup> $\pm$ 1.1	5 <sup>a</sup> $\pm$ 0.6	2.2 <sup>a</sup> $\pm$ 0.9
Low diversity	4.3 <sup>b</sup> $\pm$ 0.1	7.3 <sup>ab</sup> $\pm$ 0.9	4.9 <sup>b</sup> $\pm$ 0.0	1.1 <sup>b</sup> $\pm$ 0.1	7.4 <sup>b</sup> $\pm$ 1.6	5.4 <sup>a</sup> $\pm$ 0.8	4.2 <sup>a</sup> $\pm$ 1.2
High diversity	4.4 <sup>b</sup> $\pm$ 0.1	5.4 <sup>b</sup> $\pm$ 0.8	5.3 <sup>b</sup> $\pm$ 0.1	1.4 <sup>b</sup> $\pm$ 0.2	9.1 <sup>b</sup> $\pm$ 2.1	5 <sup>a</sup> $\pm$ 0.8	3.8 <sup>a</sup> $\pm$ 1.2
Native forest	5.5 <sup>a</sup> $\pm$ 0.2	8.8 <sup>a</sup> $\pm$ 0.3	10 <sup>a</sup> $\pm$ 1.2	2.4 <sup>a</sup> $\pm$ 0.2	29 <sup>a</sup> $\pm$ 0.0	7 <sup>a</sup> $\pm$ 0.4	0.2 <sup>b</sup> $\pm$ 0.1
<i>20-40 cm</i>							
Control	4.5 <sup>b</sup> $\pm$ 0.1	4.2 <sup>a</sup> $\pm$ 0.9	4.8 <sup>a</sup> $\pm$ 0.4	1.1 <sup>a</sup> $\pm$ 0.1	11 <sup>ab</sup> $\pm$ 2.3	4.7 <sup>a</sup> $\pm$ 1.5	3.5 <sup>a</sup> $\pm$ 0.6
Low diversity	4.3 <sup>b</sup> $\pm$ 0.0	6 <sup>a</sup> $\pm$ 1.2	4.3 <sup>a</sup> $\pm$ 0.4	0.9 <sup>a</sup> $\pm$ 0.0	8.2 <sup>b</sup> $\pm$ 1.3	4.4 <sup>a</sup> $\pm$ 1.1	5.3 <sup>a</sup> $\pm$ 0.6
High diversity	4.4 <sup>b</sup> $\pm$ 0.1	4.1 <sup>a</sup> $\pm$ 0.3	4.3 <sup>a</sup> $\pm$ 0.2	0.9 <sup>a</sup> $\pm$ 0.2	11 <sup>ab</sup> $\pm$ 2.5	4.9 <sup>a</sup> $\pm$ 1.2	3.9 <sup>a</sup> $\pm$ 0.9
Native forest	5.5 <sup>a</sup> $\pm$ 0.1	6.5 <sup>a</sup> $\pm$ 0.4	7.3 <sup>a</sup> $\pm$ 1.3	1.6 <sup>a</sup> $\pm$ 0.4	19 <sup>a</sup> $\pm$ 2.6	4.8 <sup>a</sup> $\pm$ 1.1	0.5 <sup>b</sup> $\pm$ 0.1

Means followed by the same letters in columns in each soil depth are not significantly different (Tukey test,  $P < 0.05$ ).

**Table 4.** Chemical properties in 0-5 cm soil depth; mean values (n = 3) ± standard error for the different treatments at four sampling dates during the experimental study

Properties and periods	Control	Low diversity	High diversity	Native forest
<i>OM (g dm<sup>-3</sup>)</i>				
July 1998	15.0 <sup>b</sup> ± 0.29	15.7 <sup>b</sup> ± 0.83	15.0 <sup>c</sup> ± 0.29	44.7 <sup>ab</sup> ± 0.73
August 1999	21.0 <sup>ab</sup> ± 2.17	22.0 <sup>ab</sup> ± 1.61	26.4 <sup>a</sup> ± 0.33	63.3 <sup>a</sup> ± 3.84
October 2007	25.9 <sup>ab</sup> ± 2.60	21.7 <sup>ab</sup> ± 1.42	19.5 <sup>bc</sup> ± 1.44	38.3 <sup>b</sup> ± 2.00
March 2010	30.9 <sup>a</sup> ± 4.26	26.6 <sup>a</sup> ± 1.63	24.0 <sup>ab</sup> ± 1.65	44.1 <sup>ab</sup> ± 2.28
<i>P-resina (mg dm<sup>-3</sup>)</i>				
July 1998	23.5 <sup>a</sup> ± 3.43	31.0 <sup>a</sup> ± 1.34	23.5 <sup>ab</sup> ± 3.43	33.8 <sup>a</sup> ± 1.22
August 1999	24.1 <sup>a</sup> ± 4.68	24.5 <sup>a</sup> ± 3.24	29.6 <sup>a</sup> ± 3.07	23.1 <sup>a</sup> ± 5.05
October 2007	15.1 <sup>a</sup> ± 2.61	12.9 <sup>b</sup> ± 0.35	13.1 <sup>b</sup> ± 3.95	21.9 <sup>a</sup> ± 0.79
March 2010	18.4 <sup>a</sup> ± 2.32	12.9 <sup>b</sup> ± 0.40	16.0 <sup>ab</sup> ± 0.98	20.9 <sup>a</sup> ± 0.27
<i>S-SO<sub>4</sub><sup>2-</sup> (mg dm<sup>-3</sup>)</i>				
July 1998	7.7 <sup>a</sup> ± 1.00	8.9 <sup>a</sup> ± 0.33	7.7 <sup>a</sup> ± 1.00	11.7 <sup>b</sup> ± 0.33
August 1999	5.9 <sup>b</sup> ± 0.17	4.7 <sup>b</sup> ± 0.00	4.8 <sup>b</sup> ± 0.00	9.1 <sup>b</sup> ± 0.17
October 2007	6.0 <sup>ab</sup> ± 0.48	6.7 <sup>b</sup> ± 0.61	6.1 <sup>a</sup> ± 0.75	21.7 <sup>a</sup> ± 2.11
<i>K (mmol<sub>c</sub> dm<sup>-3</sup>)</i>				
July 1998	2.4 <sup>b</sup> ± 0.07	2.1 <sup>ab</sup> ± 0.04	2.4 <sup>ab</sup> ± 0.07	8.7 <sup>a</sup> ± 0.02
August 1999	4.4 <sup>a</sup> ± 1.13	5.3 <sup>a</sup> ± 0.75	5.2 <sup>a</sup> ± 0.98	3.3 <sup>bc</sup> ± 0.13
October 2007	3.0 <sup>b</sup> ± 0.25	2.3 <sup>ab</sup> ± 0.11	3.0 <sup>ab</sup> ± 0.60	4.4 <sup>b</sup> ± 0.12
March 2010	2.2 <sup>b</sup> ± 0.25	1.3 <sup>b</sup> ± 0.05	1.6 <sup>b</sup> ± 0.20	1.9 <sup>c</sup> ± 0.17
<i>Ca (mmol<sub>c</sub> dm<sup>-3</sup>)</i>				
July 1998	16.5 <sup>a</sup> ± 0.86	20.4 <sup>ab</sup> ± 5.62	16.5 <sup>a</sup> ± 0.86	83.0 <sup>a</sup> ± 5.42
August 1999	54.8 <sup>a</sup> ± 20.8	41.2 <sup>a</sup> ± 8.37	40.4 <sup>a</sup> ± 12.5	73.7 <sup>a</sup> ± 26.2
October 2007	20.8 <sup>a</sup> ± 1.34	19.7 <sup>ab</sup> ± 1.85	24.5 <sup>a</sup> ± 3.06	89.4 <sup>a</sup> ± 15.4
March 2010	20.3 <sup>a</sup> ± 3.20	17.8 <sup>b</sup> ± 1.28	30.2 <sup>a</sup> ± 7.94	69.3 <sup>a</sup> ± 1.07
<i>Mg (mmol<sub>c</sub> dm<sup>-3</sup>)</i>				
July 1998	7.7 <sup>a</sup> ± 1.45	11.3 <sup>a</sup> ± 4.05	7.7 <sup>a</sup> ± 1.45	14.0 <sup>a</sup> ± 0.57
August 1999	20.3 <sup>a</sup> ± 5.04	15.0 <sup>a</sup> ± 3.00	12.7 <sup>a</sup> ± 2.72	17.7 <sup>a</sup> ± 3.17
October 2007	11.4 <sup>a</sup> ± 0.53	12.5 <sup>a</sup> ± 1.33	11.9 <sup>a</sup> ± 1.24	14.0 <sup>a</sup> ± 2.00
March 2010	10.5 <sup>a</sup> ± 0.89	9.2 <sup>a</sup> ± 0.89	10.5 <sup>a</sup> ± 1.84	11.1 <sup>a</sup> ± 0.67
<i>pH (CaCl<sub>2</sub>)</i>				
July 1998	5.5 <sup>ab</sup> ± 0.16	5.7 <sup>a</sup> ± 0.20	5.5 <sup>a</sup> ± 0.16	5.8 <sup>a</sup> ± 0.00
August 1999	5.6 <sup>a</sup> ± 0.06	5.5 <sup>a</sup> ± 0.06	5.6 <sup>a</sup> ± 0.06	6.1 <sup>a</sup> ± 0.19
October 2007	4.9 <sup>c</sup> ± 0.06	4.5 <sup>b</sup> ± 0.04	5.2 <sup>a</sup> ± 0.16	5.7 <sup>a</sup> ± 0.02
March 2010	5.1 <sup>bc</sup> ± 0.10	4.6 <sup>b</sup> ± 0.05	5.1 <sup>a</sup> ± 0.37	6.1 <sup>a</sup> ± 0.09
<i>Al (mmol<sub>c</sub> dm<sup>-3</sup>)</i>				
July 1998	0.1 <sup>b</sup> ± 0.10	0.1 <sup>b</sup> ± 0.07	0.1 <sup>a</sup> ± 0.10	0.7 <sup>a</sup> ± 0.20
August 1999	0.4 <sup>a</sup> ± 0.00	0.4 <sup>a</sup> ± 0.06	0.3 <sup>a</sup> ± 0.03	0.7 <sup>a</sup> ± 0.07
October 2007	0.8 <sup>a</sup> ± 0.12	1.8 <sup>a</sup> ± 0.09	0.7 <sup>a</sup> ± 0.22	0.4 <sup>a</sup> ± 0.00

Means followed by the same letters in columns in each properties and treatment are not significantly different between periods (Tukey test, P < 0.05).

the Native Forest with respect to S and Mg content. The Control differed from the Native Forest for all nutrients.

Regarding microbial biomass carbon, in March 2010 the Control, Low Diversity and High Diversity treatments showed values similar to those of the Native

**Table 5.** C and N stock and C:N ratio at 0-5 cm soil<sup>1</sup> depth and in the litter<sup>2</sup> accumulated over the ground; mean values  $\pm$  standard error for the different treatments; for soil n=3 and for litter n=48

Sink	Properties	Control	Low diversity	High diversity	Native forest
Soil	C (Mg ha <sup>-1</sup> )	10.18 <sup>a</sup> $\pm$ 0.92	8.30 <sup>a</sup> $\pm$ 0.50	7.98 <sup>a</sup> $\pm$ 0.40	11.29 <sup>a</sup> $\pm$ 1.17
	N (Mg ha <sup>-1</sup> )	0.63 <sup>b</sup> $\pm$ 0.04	0.70 <sup>b</sup> $\pm$ 0.02	0.58 <sup>b</sup> $\pm$ 0.04	1.00 <sup>a</sup> $\pm$ 0.02
	C:N	16:1 <sup>a</sup> $\pm$ 0.55	12:1 <sup>b</sup> $\pm$ 0.86	14:1 <sup>ab</sup> $\pm$ 0.27	11:1 <sup>b</sup> $\pm$ 1.01
Litter	C (Mg ha <sup>-1</sup> )	3.40 <sup>b</sup> $\pm$ 0.30	6.15 <sup>a</sup> $\pm$ 0.55	4.46 <sup>ab</sup> $\pm$ 0.45	4.35 <sup>ab</sup> $\pm$ 0.74
	N (Mg ha <sup>-1</sup> )	0.05 <sup>b</sup> $\pm$ 0.00	0.15 <sup>a</sup> $\pm$ 0.02	0.10 <sup>ab</sup> $\pm$ 0.01	0.17 <sup>a</sup> $\pm$ 0.03
	C:N	79:1 <sup>a</sup> $\pm$ 4.69	43:1 <sup>b</sup> $\pm$ 1.92	44:1 <sup>b</sup> $\pm$ 1.88	26:1 <sup>c</sup> $\pm$ 0.37

<sup>1</sup> October 2007. <sup>2</sup> average of November 2007, May and November 2008, and May 2009. Means followed by the same letter in each row are not significantly different (Tukey test,  $P < 0.05$ ).

**Table 6.** Nutrient contents in accumulated litter; mean values (n=3)  $\pm$  standard error for the different treatments

Nutrients	Control	Low diversity	High diversity	Native forest
P (g kg <sup>-1</sup> )	0.59 <sup>c</sup> $\pm$ 0.03	0.58 <sup>c</sup> $\pm$ 0.02	0.73 <sup>b</sup> $\pm$ 0.03	0.93 <sup>a</sup> $\pm$ 0.01
S (g kg <sup>-1</sup> )	1.15 <sup>b</sup> $\pm$ 0.08	1.31 <sup>ab</sup> $\pm$ 0.05	1.23 <sup>b</sup> $\pm$ 0.08	1.54 <sup>a</sup> $\pm$ 0.01
K (g kg <sup>-1</sup> )	1.53 <sup>b</sup> $\pm$ 0.19	1.23 <sup>b</sup> $\pm$ 0.17	1.55 <sup>b</sup> $\pm$ 0.08	3.40 <sup>a</sup> $\pm$ 0.66
Ca (g kg <sup>-1</sup> )	6.37 <sup>c</sup> $\pm$ 0.98	9.23 <sup>c</sup> $\pm$ 0.93	14.85 <sup>b</sup> $\pm$ 1.95	22.70 <sup>a</sup> $\pm$ 0.84
Mg (g kg <sup>-1</sup> )	1.93 <sup>b</sup> $\pm$ 0.12	2.33 <sup>ab</sup> $\pm$ 0.29	2.83 <sup>ab</sup> $\pm$ 0.14	3.10 <sup>a</sup> $\pm$ 0.21

Means followed by the same letter in each row are not significantly different (Tukey test,  $P < 0.05$ ).

Forest (Table 7). This contrasts with what was observed in July 1998 when the Native Forest showed higher contents of microbial biomass than the other treatments, except at 5-20 cm depth. Comparing data from July 1998 with those of March 2010, a trend of increasing microbial biomass through time was observed. However, the increase of microbial biomass carbon at 0-5 cm soil depth was not significant for the High Diversity treatment.

## Discussion

Differences in soil texture between the Native Forest and other treatments are probably related to the erosion process that occurred in these areas after deforestation, causing soil loss in the sandy surface layers and exposing the clay layers (Table 1). This is also a cause for the considerable decrease of organic matter content and differences between the Control, Low Diversity

**Table 7.** Microbial biomass carbon at two soil depths; mean values (n=3)  $\pm$  standard error for the different treatments at four sampling periods

Depths and periods	Control (mg C g soil <sup>-1</sup> )	Low diversity (mg C g soil <sup>-1</sup> )	High diversity (mg C g soil <sup>-1</sup> )	Native forest (mg C g soil <sup>-1</sup> )
<i>0-5 cm</i>				
July 1998	0.071 <sup>bB</sup> $\pm$ 0.020	0.060 <sup>bB</sup> $\pm$ 0.030	0.071 <sup>aB</sup> $\pm$ 0.020	0.234 <sup>bA</sup> $\pm$ 0.017
January 1999	0.188 <sup>abB</sup> $\pm$ 0.015	0.145 <sup>abB</sup> $\pm$ 0.015	0.086 <sup>aB</sup> $\pm$ 0.005	0.492 <sup>aA</sup> $\pm$ 0.028
October 2008	0.147 <sup>ba</sup> $\pm$ 0.017	0.137 <sup>abA</sup> $\pm$ 0.014	0.140 <sup>aA</sup> $\pm$ 0.020	0.263 <sup>abA</sup> $\pm$ 0.065
March 2010	0.273 <sup>aa</sup> $\pm$ 0.027	0.240 <sup>aA</sup> $\pm$ 0.030	0.160 <sup>aA</sup> $\pm$ 0.038	0.355 <sup>aA</sup> $\pm$ 0.078
<i>5-20 cm</i>				
July 1998	0.071 <sup>cA</sup> $\pm$ 0.020	0.037 <sup>ba</sup> $\pm$ 0.025	0.071 <sup>ba</sup> $\pm$ 0.020	0.025 <sup>cA</sup> $\pm$ 0.010
January 1999	0.296 <sup>aA</sup> $\pm$ 0.008	0.345 <sup>aA</sup> $\pm$ 0.024	0.206 <sup>aB</sup> $\pm$ 0.003	0.220 <sup>aB</sup> $\pm$ 0.014
October 2008	0.077 <sup>cB</sup> $\pm$ 0.012	0.107 <sup>bAB</sup> $\pm$ 0.017	0.125 <sup>abAB</sup> $\pm$ 0.029	0.170 <sup>bcA</sup> $\pm$ 0.010
March 2010	0.190 <sup>ba</sup> $\pm$ 0.011	0.137 <sup>ba</sup> $\pm$ 0.018	0.127 <sup>abA</sup> $\pm$ 0.019	0.175 <sup>abA</sup> $\pm$ 0.009

Means followed by the same lowercase letter in each column and depth, and means followed by the same uppercase letter in the same row are not significantly different (Tukey test,  $P < 0.05$ ).

and High Diversity treatments relative to the Native Forest in terms of chemical properties (Table 3). Cerri *et al.* (1991) and Gregorich *et al.* (1998) attributed the deterioration of soil physical, chemical and biological properties after deforestation to reduction of soil organic stocks due to changes in its use and erosion. In both restoration models and in the Control, the reduction of bulk density and consequent increase in porosity (Table 2) may have been caused by the growth of the planted trees and natural regeneration (Engel and Parrotta, 2001; Siddique *et al.*, 2008). After the protection and reforestation of the study site, the increase of organic matter content (Table 4), through litterfall and root growth, may have been the main agent of this change. The reduction of sand content in the Low Diversity treatment may be explained by the greater presence of macroorganisms in this treatment (Ducatti, 2002), which could have modified the textural composition, or to the result of erosion that may have prevailed in this treatment.

One of the study hypotheses is that the mixed plantings preserve important soil physical properties in the process of restoration of degraded ecosystems. Data collected so far do not allow confirmation of this hypothesis, because soil changes are still occurring, especially in texture of the Low Diversity treatment. Moreover, the bulk density and porosity may be suffering effects of more rapid forest stand development. While small changes of texture in the surface layers are still occurring, this should not limit the recovery of soil fertility (Table 2 and 4). The good structural conditions of the soil (Oliveira, 1999) associated with the predominance of mixed mineralogy (Fe and Al sesquioxide and clay 1:1) and its current fertility should promote the restoration of important physical (bulk density and porosity), chemical (pH, organic carbon, N, P, S, K, Ca and Mg) and biological properties (macro-, meso- and micro-organisms). Because the soils of the study site are of medium fertility and showed lower nutrient content than those of natural condition at the beginning of experiment, the return to pre-existing conditions will be slow and dependent on the nutrient cycling process.

Paul *et al.* (2010) studied the recovery of soil properties and functions in different reforestation models in Australia and found significant variation and specific patterns among areas and reforestation models. For these authors, the reforestation models (ecological restoration planting, camphor-dominated, and treated camphor), more or less complex, were able to recover

(more favorable) soil properties to different degrees, specifically pH, bulk density and available phosphorus. The variation in soil nutrient contents and quality of accumulated litter (Table 4 and 6) support the findings of their study that restoration models may contribute differently to changes of soil chemical properties. However, changes in soils occurred earlier in the Low Diversity treatment than in other treatments (Table 4), which may indicate higher rates of nutrient cycling promoted by species composition (Siddique *et al.*, 2008) and by more rapid establishment of forest structure (Engel and Parrotta, 2001). Another factor that may have contributed to the differences between restoration models is the soil preparation methods used, *i.e.*, the minimal cultivation employed in the Low Diversity treatment and the conventional tillage employed in the High Diversity treatment.

The results for C and N stocks can be compared to those obtained by Macedo *et al.* (2008). These authors studied changes in C and N stocks thirteen years after reforestation in degraded land in Atlantic Forest where nitrogen-fixing legume trees had been planted. At 0-5 cm soil depth, stocks of 10.9 Mg C ha<sup>-1</sup> and 0.94 Mg N ha<sup>-1</sup> were found. These are slightly higher than those in our study (Table 5), though similar soil C:N ratios were found in both studies. In native forests, values for C and N stocks were 12 and 1.17 Mg ha<sup>-1</sup>, respectively, levels similar to those of in the Native Forest in our study. Similarly, these authors found that the soil properties evaluated in the recovery area were similar to those of the native forest. Generally, a lower soil C:N ratio, common in soils under native forests and found in the Low Diversity and High Diversity treatments, indicate a high biological nitrogen fixation, and pronounced deposition of organic matter and nutrient cycling (Parrotta, 1999; Macedo *et al.*, 2008). According to Pulito (2009), total N can be considered as a good indicator of N availability in the soil.

For both restoration models in relation to the Control, the lower C:N ratio in accumulated litter indicated the pronounced effect of the models in terms of biological nitrogen fixation, especially in the Low Diversity treatment, which has a higher density of N<sub>2</sub>-fixing leguminous trees (Siddique *et al.*, 2008). These authors studied the dominance of leguminous trees and relationships among nutrients seven years after the plantations were established, comparing the Low Diversity and High Diversity treatments. Their results showed that the two models diverged in terms of N and P. Within seven years, the dominance of a single



species of N<sub>2</sub>-fixing tree (*Enterolobium contortisiliquum*) in the Low Diversity treatment resulted in rapid biomass accumulation and higher concentrations of N in the biomass and in the litter, compared to the High Diversity treatment with its lower density of N<sub>2</sub>-fixing trees. Soil nitrate values in the Low Diversity treatment were six times higher than those in the High Diversity treatment, reducing the availability of P in the soil as a result of high N concentrations in leaves and more conservative P ratio in the leaves of the other two species (*Psidium guajava* and *Peschiera fuchisiaefolia*) that regenerated naturally in both systems. That is, the faster tree growth in the Low Diversity treatment could be immobilizing a large amount of P in the biomass and thereby reducing P in the soil among July 1998 and March 2010, as shown in Table 4. Therefore, it is suggested that P-fixing tree species could be introduced in such restoration models to improve soil P status. The higher soil C stock in the Control may be related to residual organic matter from the dominant grasses that have a high C:N ratio, which indicates a low rate of organic matter decomposition, or a high C content in grass biomass.

The Low Diversity and High Diversity treatments have promoted favorable conditions for the development of soil microorganisms once the organic matter content gradually increased in both models (Table 4), and soil C:N ratio was similar to that in the Native Forest (Table 5). This can be corroborated by the increase of microbial biomass carbon (Table 7), especially in the Low Diversity treatment. For Harris (2009), microorganisms have critical roles in the functioning of soil in nutrient cycling, structural formation, and plant-soil interactions, both positive and negative. This is of fundamental importance for the reestablishment of structure and function in restoring degraded lands. Moreover, the microbial biomass represents the greater part of the active fraction of the organic matter, being sensitive to changes in content and quality of soil organic matter (Gama-Rodrigues, 1999) and may be used as a useful indicator of forest management of organic matter quality in the soil (Mahía *et al.*, 2006). In part, the chemical and biological properties in this study showed changes in soils towards their original conditions of natural fertility in both the restoration models as well as in the Control treatment. This recovery will be facilitated by nutrient cycling, and influenced by the quantity and quality of organic matter input to the soil, through the further development of planted and naturally regenerated trees and other plant species in

the different restoration models and natural regeneration treatments.

## Conclusions

The results showed that vegetation establishment on degraded land, independent of the tree species diversity of the restoration model used, leads to soil texture preservation and improvements in bulk density and porosity. After ten years, the increases in soil organic carbon and the C:N ratio, along with increased microbial biomass, indicate that the nutrient cycling process is being enhanced. Moreover, restoration models with either low and high diversity of planted native species (as well as the natural regeneration occurring in these stands) can all facilitate the recovery of chemical and biological properties of degraded soils. However, during the initial 10-year phase of restoration of this degraded site, the model with low diversity of planted species promoted faster changes in soil properties as a result of more rapid tree growth and stand development after planting.

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