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Can intensive management accelerate the restoration of Brazil's Atlantic forests?

Otávio Camargo Campoe [a,*], José Luiz Stape [b,1], João Carlos Teixeira Mendes [a,2]

[a] University of São Paulo, Department of Forest Sciences, Piracicaba, SP 13418-970, Brazil
[b] North Carolina State University, Department of Forestry and Environmental Resources, Raleigh, NC 27695-8008, USA

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ABSTRACT

Only 7% of the once extensive forest along the eastern coast of Brazil remains, and much of that is degraded and threatened by agricultural expansion and urbanization. We wondered if methods similar to those developed to establish fast-growing Eucalyptus plantations might also work to enhance survival and growth of rainforest species on degraded pastures composed of highly competitive C_4 grasses. An 8-factor experiment was laid out to contrast the value of different intensities of cultivation, application of fertilizer and weed control on the growth and survival of a mixture of 20 rainforest species planted at two densities: 3 m × 1 m, and 3 m × 2 m. Intensive management increased seedling survival from 90% to 98%, stemwood production and leaf area index (LAI) by ~4-fold, and stemwood production per unit of light absorbed by 30%. Annual growth in stem biomass was closely related to LAI alone ($r^2 = 0.93$, $p < 0.0001$), and the regression improved further in combination with canopy nitrogen content ($r^2 = 0.99$, $p < 0.0001$). Intensive management resulted in a nearly closed forest canopy in less than 4 years, and offers a practical means to establish functional forests on abandoned agricultural land.

1. Introduction

Three hundred years ago, the Brazilian Atlantic area supported forest ecosystems with productivity and diversity that matched that in the Amazon Basin (Mittermeier et al., 1999; FAO, 2009). These forests consisted of three distinct types: evergreen, seasonally deciduous and widely spaced gallery woodlands (Morellato and Haddad, 2000). They ranged from 4° to 32°S and covered a total of 1.2 million km^2 (SOS Mata Atlântica and INPE 2008). Relicts of this once great expanse of forest still rank among the 25 most important international areas for biodiversity, supporting >20,000 species of vascular plants. Forty percent of these plants are endemic, representing 2.7% of the planet's total (Mittermeier et al., 1999; Myers et al., 2000). Deforestation continues to convert remaining patches of Atlantic forest to agricultural and urban land uses at a rate of 0.5% per year (Brooks et al., 2002; SOS Mata Atlântica and INPE 2008). At present, only 7.6% of the original Atlantic Forest remains intact (Tabarelli et al., 2005; SOS Mata Atlântica and INPE 2008).

In some cases, if a seed source is available, native rainforest are able to re-establish naturally on abandoned agricultural lands (Lamb, 1998). This process, however, is slow (Finegan, 1996; Martins and Engel, 2007). In many places, even where an adequate seed source is present, soil compaction, nutrient depletion, and competition from introduced C_4 grasses prevent seedlings from ever establishing (Engel and Parrotta, 2001; Parrotta and Knowles, 2001; Doust et al., 2008; Laliberté et al., 2008).

As an alternative to relying on natural processes, some have suggested that intensive site preparation should reduce competition from grasses while increasing survival and growth rates of planted or naturally established tree seedlings (Parrotta et al., 1997; Singh et al., 2000; Florentine and Westbrooke, 2004; Lamb et al., 2005; Laliberté et al., 2008).

Although seedling survival and growth are essential prerequisites to reclaim abandoned agricultural land, they are no guarantee that a self-perpetuating rainforest will develop. Speed is essential to achieve full canopy development in order to minimize surface desiccation during the normal dry season, and to permit roots to reach depths where moisture is available to sustain trees through periodic droughts.

Canopy development differs among the native forests of the Atlantic area. Trees grow faster and develop a denser canopy in favorable than in unfavorable environments. For this reason, the canopy leaf area index (LAI) is a key variable for reference in assessment of techniques designed to re-establish rainforests (Waring, 1983). The amount of nitrogen accumulated in a forest canopy is also a useful measure of its photosynthetic capacity (Chapin et al., 1987). Competition for light and other resources reduce the growth efficiency of individual trees. A good measure of

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[*] Corresponding author. Tel.: +55 19 2105 8689; fax: +55 19 2105 8601.
E-mail addresses: occampoe@esalq.usp.br (O.C. Campoe), jlstape@ncsu.edu (J.L. Stape), jctmende@esalq.usp.br (J.C.T. Mendes).
[1] Tel.: +1 919 513 4041.
[2] Tel.: +55 19 2105 8689; fax: +55 19 2105 8601.

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the intensity of competition for individuals, or for whole communities, is stemwood production per unit of light absorbed, termed light use efficiency (LUE) (Monteith, 1972).

In this paper, we report results of an experiment to establish a mixture of 20 rainforest species on a degraded pasture using both traditional and more intensive management techniques. We follow stand development over a 3.5-year period to contrast changes in the rates of stemwood biomass growth (ΔB), LAI, and LUE.

2. Materials and methods

2.1. Site description

The trial was installed at the University of São Paulo's Anhembi Forest Research Station (22°43′22″S, 48°10′32″W) situated at an elevation of 460 m on a 2% slope. The research station is located within the Atlantic Forest biome, which is dominated by a semi-deciduous seasonal forest (Cesar, 1988). Over the 3.5 years of the study, mean, maximum and minimum monthly temperature averaged 19.1 °C, 24.2 °C, and 14.1 °C, and rainfall averaged 1170 mm year^{-1}, with 75% falling between October and March. During the dry season (May to August), the water deficit averaged 48 mm. The soil type in the area is an acidic (pH 4.0) Typic Hapludox, comprised of 5% silt, 13% clay and 82% sand, with relatively low organic matter (1%, in the top 20 cm).

2.2. Experimental design

In March, 2004, we planted mixtures of 20 tree species native to this part of Brazil (Assunção et al., 1982; Cesar, 1988, Table 1), after controlling African signal grass (*Brachiaria decumbens*) through cultivation and application of 5 L ha^{-1} of glyphosate (0.2%) on all treatments. Control of leaf-cutter ants (*Atta* sp. and *Acromyrmex* sp.) was accomplished by systematic placement of baits (0.3% of sulfluramid), throughout the experimental area.

We installed a 2 × 2 × 2 factorial design: (a) by varying the ratio of pioneer to later colonizing species (50:50 versus 67:33); (b) by modifying spacing (3 m × 1 m versus 3 m × 2 m); and (c) by altering the intensity of management to control weeds and to accelerate seedling growth through addition of inorganic fertilizers. Each combination of treatments was replicated 4 times in randomized blocks; each plot was 42 m × 30 m (1260 m^2) to provide a buffer, with an interior plot of 36 m × 22 m (792 m^2) on which measurements were made. Four additional plots were established to provide trees of different sizes that could be sampled destructively to develop allometric biomass equations.

By increasing the fraction of pioneer species from 50% to 67% of the mix, we expected lower rates of seedling mortality and slightly increased rates of growth. With the higher planting density (3333 plants ha^{-1} versus 1667 plants ha^{-1}), we sought to speed canopy closure, although competition among trees was expected to increase compared with surviving seedling planted at the lower density.

Traditional procedures for the establishment of tree seedlings on abandoned pastures include repeated weeding of signal grass within planting rows (±50 cm), mechanized chopping between rows (at 6, 12, 18 and 24 months after planting) and the addition of moderate amounts of fertilizer near each seedling in the first year (March and September of 2004), totaling per hectare 27 kg N, 21 kg P, 11 kg K and 24 kg Ca.

In contrast, the intensive treatment sought to eliminate all grass competition by spraying every 3 months for the first 2 years with 5 L ha^{-1} of glyphosate (0.2%) across the entire plot, followed by spot applications where necessary. Fertilizer was applied not only at the time of planting (March 2004), but annually, resulting in a total application per hectare of 81 kg N, 62 kg P, 33 kg K, 452 kg Ca and 180 kg Mg. This amount of fertilizer is more than 3 times of the traditional, but less than half that applied to commercial plantations of eucalyptus (Gonçalves et al., 2004; Stape et al., 2006).

2.3. Stemwood biomass and growth

Heights and diameters (at 0.3 m height) were measured on all trees inside the plot buffer strips at the end of the first and second years, and henceforth every 6 months until the termination of the experiment. We estimated bole biomass based on cross-sectional area, total height, stem taper and wood density, derived from equations based on destructive harvesting of 10 representative trees of each of the 20 species (Campoe, 2008, Table 1). By summing the biomass (B) of all stems (including bark), plot biomass was obtained and expressed on a per hectare basis. Growth (ΔB) was calculated annually as stem biomass accumulated.

2.4. Additional measures of stand structure and function

Canopy dynamics, including trees and other vegetation, was quantified in March 2007 (wet season) and in September 2007 (dry

Table 1
Taxonomic and ecological characteristics of 20 selected Atlantic forest species for the experiment.

Scientific name	Abbreviation	Family	Successional status	Reclassification	Wood density (kg m^{-3})	Taper factor
Acacia polyphylla	MO	Mimosoideae	Pioneer	Fast	650 ± 70	0.55 ± 0.14
Cariniana estrellensis	JE	Lecythidaceae	Non-pioneer	Slow	390 ± 40	0.52 ± 0.20
Cedrela fissilis	CE	Meliaceae	Non-pioneer	Slow	310 ± 50	0.60 ± 0.11
Chorisia speciosa	PA	Malvaceae	Non-pioneer	Intermediary	200 ± 10	0.40 ± 0.12
Croton urucurana	SD	Euphorbiaceae	Pioneer	Fast	340 ± 30	0.49 ± 0.12
Enterolobium contortisiliquum	TI	Mimosoideae	Pioneer	Intermediary	240 ± 40	0.52 ± 0.09
Erythrina mulungu	ML	Papilionoideae	Pioneer	Fast	270 ± 20	0.44 ± 0.06
Ficus guaranitica	FB	Moraceae	Non-pioneer	Fast	340 ± 80	0.58 ± 0.14
Guazuma ulmifolia	MT	Malvaceae	Pioneer	Fast	410 ± 40	0.46 ± 0.13
Heliocarpus americanus	AL	Tiliaceae	Pioneer	Fast	290 ± 30	0.43 ± 0.08
Hymenaea courbaril	JT	Caesalpinioideae	Non-pioneer	Intermediary	500 ± 20	0.44 ± 0.08
Jacaranda cuspidifolia	JA	Bignoniaceae	Non-pioneer	Intermediary	360 ± 20	0.56 ± 0.10
Lafoensia pacari	DE	Lythraceae	Non-pioneer	Intermediary	510 ± 30	0.54 ± 0.12
Luehea divaricata	AC	Tiliaceae	Pioneer	Intermediary	360 ± 10	0.49 ± 0.08
Myroxylon peruiferum	CB	Papilionoideae	Non-pioneer	Slow	480 ± 40	0.61 ± 0.25
Peltophorum dubium	CF	Caesalpinioideae	Pioneer	Fast	450 ± 40	0.54 ± 0.13
Poecilanthe parviflora	LA	Papilionoidade	Non-pioneer	Slow	620 ± 110	0.58 ± 0.13
Pterogyne nitens	AM	Caesalpinioideae	Pioneer	Intermediary	540 ± 40	0.62 ± 0.16
Schinus terebinthifolia	AP	Anacardinaceae	Pioneer	Fast	440 ± 20	0.52 ± 0.15
Tabebuia impetiginosa	IR	Bignoniaceae	Non-pioneer	Fast	420 ± 30	0.46 ± 0.07

season) using hemispheric photographs analyzed with the software Hemisfer 1.41 (Schleppi et al., 2007). The fraction of sky visible in the hemispheric photographs was converted to LAI through a calibration scheme proposed by Clark et al. (2008) that involves destructive sampling, as detailed below. The calibration between sky light and leaf area explicitly excluded light intercepted by bole, branches, twigs, flowers and fruits. Hemispherical photographs were taken before 10:30 and after 15:30 h using a FUJI FinePix S5000 camera with a fish-eye lens (Opteka, 0.22X, AF), providing 175° coverage (colors sRGB, F-stop 5.6, aperture time from 1/50 to 1/250), creating a 6 megapixel image (2816 × 2120 pixels). The camera was mounted on a tripod, positioned 0.6 m above ground level, focused upward, with the top toward magnetic north and maintained horizon with bubble level. Six photographs were taken on each of the 32 plots, spaced systematically, 10–15 m away from plots borders to avoid confounding the image with the effect of other treatments.

More intensive measurements were taken on 8 plots that displayed a wide range of LAI values (ranging from 0.5 to 3.0) to acquire data for the calibration. All live leaves were collected from ground level to the top of the canopy projected above four, 1.5 m × 1.5 m areas marked off on the ground surface. The collected leaves were kept cool for up to 2 days, when they were taken to the laboratory and their one-sided projected area was measured with a LI 3100 (LI-COR, Lincoln, NE, USA). The subsequent equation developed to predict LAI from fish-eye images was highly significant ($r^2 = 0.73$, $P < 0.0001$, $n = 32$) (more details about the methods implemented on Hemisfer 1.41 software are provided by Norman and Campbell (1989) and by Nobis and Hunziker (2005).

In March, 2007, light extinction coefficients (k) were determined from light interception measured between 10:30 and 14:30 h at the same points used to calibrate the fish-eye images. Measurements of light (photosynthetically active radiation, PAR) transmission were registered with a ceptometer AccuPAR (Decagon Devices Inc., 1999) and compared with incident PAR measured in the open (Bréda, 2003). With calibrated estimates of LAI and measurements of absorbed PAR on each plot, we used the Lambert–Beer Law to calculate k.

$$k = -\ln \frac{(I/I_0)}{\mathrm{LAI}} \qquad (1)$$

where k is the light extinction coefficient, LAI is leaf area index, I is PAR radiation transmitted through canopy and I_0 is the incident radiation above the canopy. The k was calculated for each plot as the linear mean of the 4 positions because it is site specific and vary with leaf angle, shape and clumping (Gower et al., 1999).

The PAR radiation incident at experimental area (TJ ha^{-1} month^{-1}), March to September of 2007 was used to calculate absorbed photosynthetically active radiation (APAR, TJ ha^{-1} semester^{-1}), for each plot based on Runyon et al. (1994) and Gower et al. (1999):

$$\mathrm{APAR} = \sum_{i=1}^{6} [\mathrm{PAR}_i (1 - e^{-k\,\mathrm{LAI}_i})] \qquad (2)$$

LAI measured in March was assumed maintained until June, because water remained near field capacity during this period (data not shown). For July and August, a linear decline in LAI was assumed in response to increasing water deficit, until September, when LAI was re-measured in the middle of the dry season.

The percentage of nitrogen in leaves (N, g kg^{-1}) was determined by Kjeldahl digestion on sub-samples of leaves acquired during the destructive sampling of trees. The nitrogen content of the canopy, $\mathrm{N}_{\mathrm{canopy}}$, expressed as g N m^{-2} of ground, was calculated based on LAI (determined by destructive sampling) and specific leaf area (SLA, which ranged from 3.2 to 18.5 m^2 kg^{-1}, Iannelli-Servín, 2007), according to the equation:

$$\mathrm{N}_{\mathrm{canopy}} = \mathrm{N}\left(\frac{\mathrm{LAI}}{\mathrm{SLA}}\right) \qquad (3)$$

2.5. Statistical analyses

One-way analysis of variance (GLM procedure) was used to compare independent effects and interactions between species composition, spacing and management on ΔB, LAI, APAR, LUE and $\mathrm{N}_{\mathrm{canopy}}$. In case of significant interactions, Tukey's Student Range

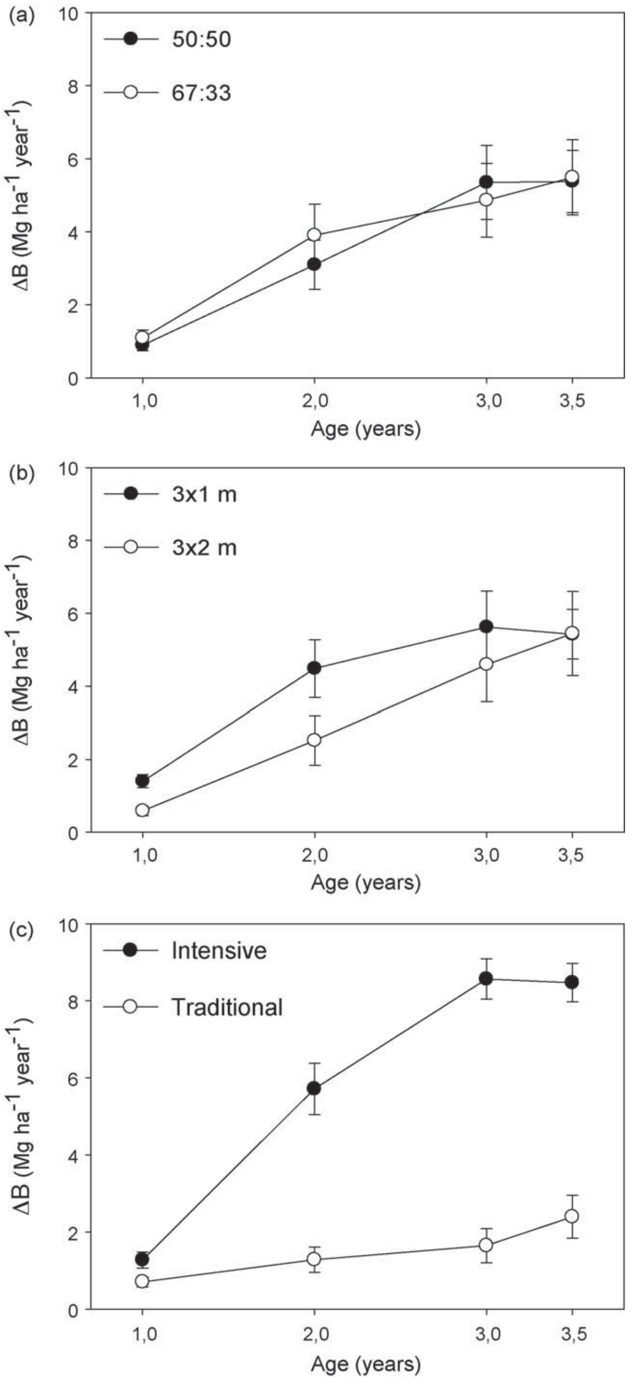

Fig. 1. Stemwood production (ΔB) in response to different treatments: (a) mixture of pioneer to other tree species, (b) narrow and wide spacing, and (c) intensive and traditional site preparation. Error bar = standard error of the mean; N = 16 for each treatment.

Fig. 2. Rainforest plantations under traditional (left) and intensive (right) management after 3 years. The calibrated hemispherical photographs on the left yields an LAI of 0.5 for all vegetation, with the tallest trees reaching a height of 4 m. On the right, the LAI is 1.7, the trees are 10 m tall, and there is little competition from grass.

Test (HSD) was used with the level of significance set at 0.05 (control of error Type I). All the analysis were made using SAS 9.1 (SAS Institute Inc., Cary, NC, USA). We examined relations between the independent variables (LAI, APAR, LUE and N_{canopy}) and ΔB with simple linear regression analyses using SigmaPlot (Systat Software Inc., San Jose, CA, USA).

3. Results

Higher proportion of pioneer species (67% versus 50%) did not significantly alter the rate of biomass accumulation throughout the study (Fig. 1a). Although stem biomass initially accumulated at a faster rate under the higher level of stocking (3 m × 1 m versus 3 m × 2 m), there were no significance differences by the third year (Fig. 1b). The overriding benefits of intensive management on stemwood growth rates are apparent in Fig. 1c, where the differences exceed 4-fold by the end of the experiment, with an accumulated biomass of 18.6 Mg ha^{-1} versus 4.6 Mg ha^{-1}. The visual differences in tree size and canopy development are pictured in Fig. 2.

More pioneer species (67%) slightly increased LAI only on the wet season, becoming similar on the dry season (Table 2). Denser spacing, with two times more trees per hectare increased LAI on average of 35% on both seasons. Nevertheless, the silvicultural improvements generated by the intensive management increased ~4-fold LAI, being more significant at dry season (Table 2).

The composition with higher proportion of pioneers did not lead to an expressive increase on APAR, LUE and N_{canopy}. Absorbed PAR was higher in the denser plots (7.8 TJ ha^{-1} semester^{-1} versus 6.2 TJ ha^{-1} semester^{-1}), but LUE was not altered with plant stocking. With twice as many trees per hectare and higher LAI, N_{canopy} was 92% higher. The gain in APAR was great under intensive management, absorbing 4.8-fold more PAR (11.6 TJ ha^{-1} semester^{-1} versus 2.4 TJ ha^{-1} semester^{-1}). LUE increased 29% due to intensive silviculture. Also nitrogen on the canopy was higher with intensive management (5.25 g m^{-2} versus 2.13 g m^{-2}), a 147% increase.

Stem biomass growth rate correlated with all the canopy characteristics (LAI, LUE and N_{canopy}). Overall, a 0.5 increase in LAI leaded to an increase of 2.8 Mg ha^{-1} year^{-1} on ΔB (Fig. 3a). The positive relation between LUE and ΔB (Fig. 3b) indicated that productive, high-LAI treatments also had higher efficiency in light use. Canopy nitrogen related moderately with ΔB (Fig. 3c), due in part to the inclusion of nitrogen-fixing species (Leguminosae, Table 1). A combination of LAI and N_{canopy} improved the prediction capability of ΔB (Fig. 4, $r^2 = 0.99$, $P < 0.0001$).

Despite the interaction analysis among the factors (composition, spacing and silviculture) and studied variables (ΔB, LAI, APAR, LUE and N_{canopy}), most of them showed poor significance levels ($P > 0.15$), except by spacing × silviculture for ΔB and LUE ($P < 0.0001$, Fig. 5).

Seedlings survival was increased from 90% to 98% by the site improvement of the intensive silvicultural management. Nineteen of the 20 native species showed positive response on their productivity (Fig. 6), resulting an average increase on ΔB of 2.7-fold. Among the pioneer species, *Pterogyne nitens* (AM, Leguminosae) was the most responsive, increasing ΔB by 24.5-fold (from 0.04 to 0.98 Mg ha^{-1} year^{-1}). Among non-pioneer species, *Cariniana estrellensis* (JE) showed 5-fold increase in ΔB (from 0.03 to 0.15 Mg ha^{-1} year^{-1}).

Table 2

Stemwood production (annual), leaf area index, for wet and dry season, absorbed PAR (semi-annual), light use efficiency (semi-annual) and nitrogen at the canopy. Values (within columns) followed by different letters differ at $p = 0.05$.

Factors	Levels	ΔB 3.5 years (Mg ha^{-1} year^{-1})	Leaf area index (m^2 m^{-2})		Absorbed PAR (TJ ha^{-1} semester^{-1})	Light use efficiency (g ΔB MJ^{-1} APAR)	N_{canopy} (g m^{-2} of ground)
			wet season (3 years)	dry season (3, 5 years)			
Composition	50:50	5.5 a	1.17 a	0.62 a	7.3 a	0.24 a	3.28 a
	67:33	5.4 a	1.01 b	0.56 a	6.7 a	0.24 a	4.11 a
Spacing	3 m × 1 m	5.5 a	1.27 a	0.67 a	7.8 a	0.23 a	4.86 a
	3 m × 2 m	5.5 a	0.91 b	0.51 b	6.2 b	0.25 a	2.53 b
Management	Traditional	2.4 b	0.47 b	0.22 b	2.4 b	0.21 a	2.13 b
	Intensive	8.6 a	1.71 a	0.96 a	11.6 a	0.27 a	5.25 a

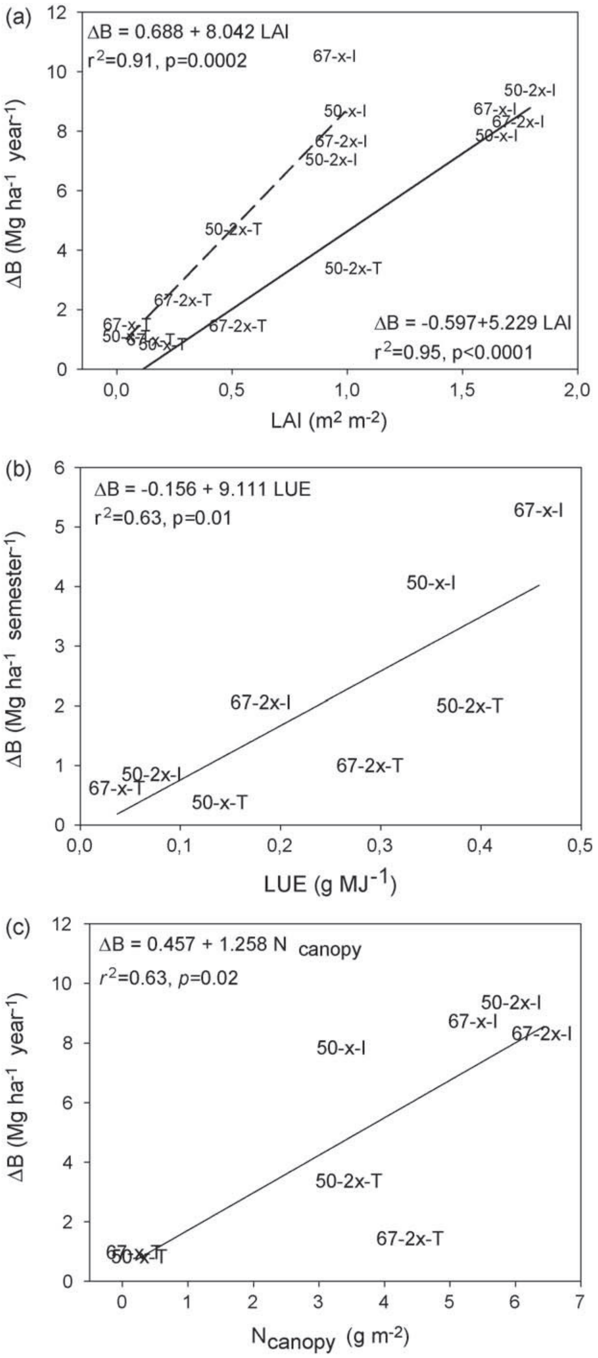

Fig. 3. Stemwood growth (ΔB) increased linearly as a function of: (a) LAI measured at 3 years (- -) and 3.5 years (——), (b) LUE, and (c) N_{canopy}. Abbreviations: T, traditional and I, intensive treatments; x, 3 m × 2 m and 2x, 3 × 1 spacing; 50, 50:50 and 67, 67:33 species mix of pioneer versus other types.

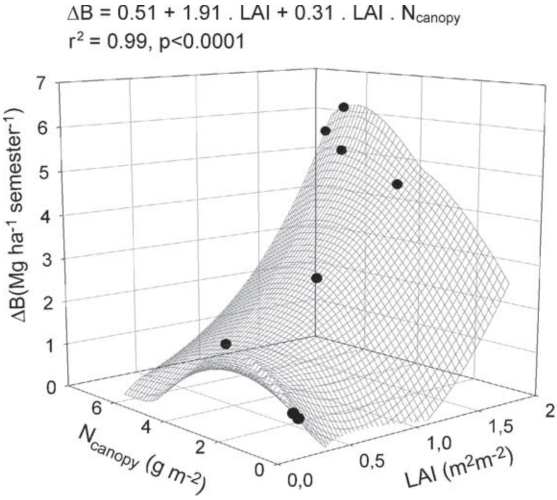

Fig. 4. Based on 8 treatments, a relation between leaf area index (LAI) and canopy nitrogen content (N_{canopy}) describes a tipped-up tent-like surface (gray net) that accounts for nearly all observed variation in stemwood production (ΔB) for the study.

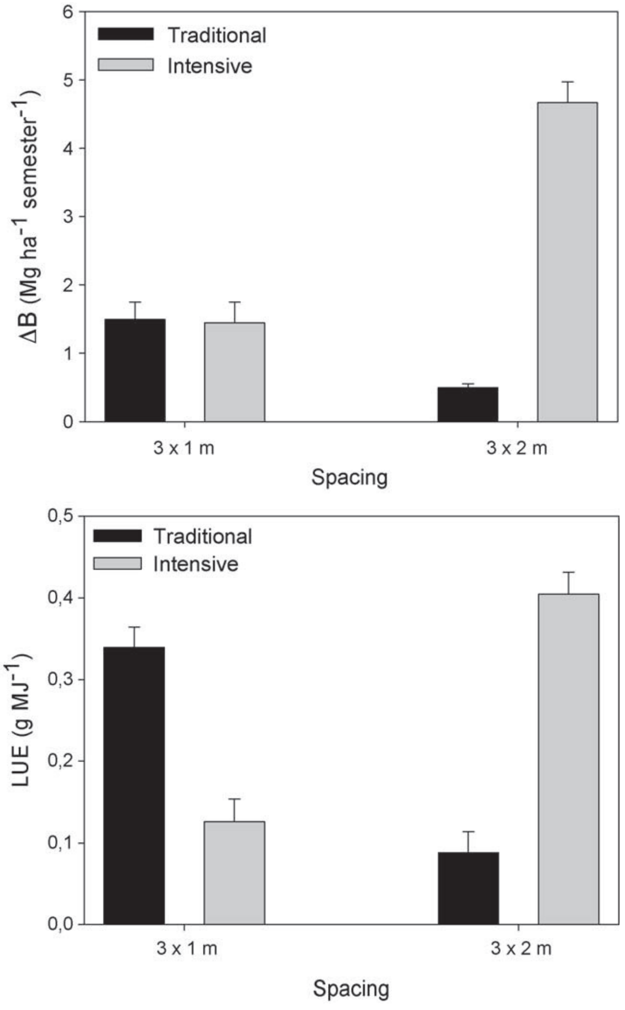

Fig. 5. The intensity of management had no effect on ΔB over the last 6 months of the study at high stocking densities (upper), although trees provided traditional treatments had much higher LUE values (lower). In contrast, at wider initial stocking levels, both ΔB and LUE increased by >4-fold under intensive management.

4. Discussion

Native species plantations in different climatic zones have shown that pioneers and early secondary species typically grow faster than late successional species (Florentine and Westbrooke, 2004; Santos et al., 2006). This general expectation did not happen in our experiment (Fig. 1a, Table 2), also observed by Delagrange et al. (2008).

The classification of Brazilian native tree species in different successional groups is based on Budowski (1965), and the theory of gap dynamics on tropical forests. When a gap is generated at a forest canopy, and the sun reach ground level changing micro-

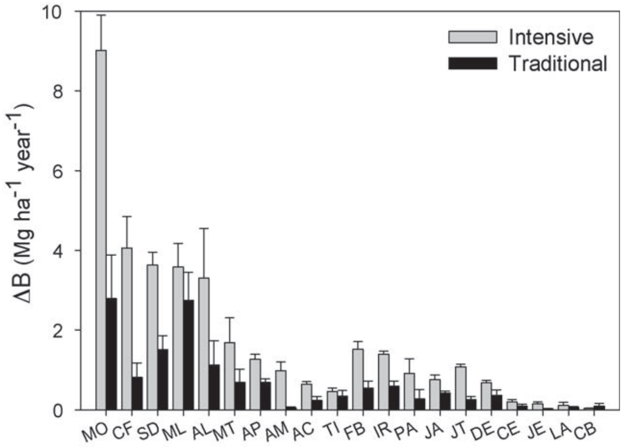

Fig. 6. Differential stemwood production (ΔB) by 20 native species in response to intensive and traditional site preparation. Pioneer species in TI and all listings to the left; non-pioneers start with FB and continue to the right. The bars represent standard errors of the mean based on $N = 4$.

climate within, the first species that re-colonize the area are pioneers (shade intolerant) and then, after canopy closure, non-pioneers (Withmore, 1990). On our restoration plantation the species showed different growth patterns from that proposed by Budowski. Therefore, the application of his classification method was not adequated to characterize the succession class of the species under restoration plantation conditions, where the environment is distinct from a gap dynamic inside the natural forest (Lugo and Lowe, 1995). In a degraded area, light-, thermal-, nutritional-, water- and competition-stresses may influence the behavior of the species under traditional- and intensive-silvicultural practices (higher and lower stress levels).

The purpose of higher pioneer proportion was to provide a shade environment for the non-pioneer species (shade tolerant), resulting on early canopy closure and inhibition of weeds, catalyzing the restoration process (Parrotta et al., 1997; Lamb, 1998; Florentine and Westbrooke, 2004). Because the response did not reach such expectations, and the development of both pioneer and non-pioneer proportion was equivalent, the species were reclassified according to their behavior under restoration plantation conditions as fast, intermediate and slow growing (Table 1), to guide species selection for future forest restoration of Atlantic Forest, as done by Sampaio et al. (2007). Besides that, the use of less pioneers (50%) should be recommended due to the higher proportion of long-lived non-pioneer species, which will increase the forest biodiversity (Kageyama et al., 2003).

Until the second year, ΔB was twice as much on denser spacing due to the higher stocking (3333 trees ha^{-1} versus 1667 trees ha^{-1}), leading to more stem biomass accumulation at the last year (13.0 Mg ha^{-1} versus 10.3 Mg ha^{-1}). However, after the third year ΔB became similar, imposed by a higher level of competition among trees (Fig. 1b), dropping the LUE under intensive silviculture (Fig. 5), probably due to higher LAI (Table 2) associated with a strong competition for water during the dry season (Henskens et al., 2001).

In this study (Fig. 1b) and similar to Henskens et al. (2001) and Grant et al. (2006), achieve similar growth rates with lower stocking would have great implications on forest restoration activities, reducing seedling demand, decreasing plantation costs and increasing economic viability (Engel and Parrotta, 2001; Lamb et al., 2005).

The interaction between stocking and silviculture, for ΔB and LUE ($p < 0.0001$, Fig. 5), denote an important practical application of this study. At 3 m × 1 m spacing, both levels of silviculture had equivalent ΔB (1.5 Mg ha^{-1} semester^{-1}), but for the 3 m × 2 m spacing, intensive management obtained 9.4-fold gain over traditional (4.7 Mg ha^{-1} semester^{-1} versus 0.5 Mg ha^{-1} semester^{-1}). In terms of LUE, 3 m × 1 m is 2.6-fold more efficient when managed traditionally, while on 3 m × 2 m, intensive manage overcome traditional 3-fold. These results show that wider spacing is totally dependent of intensive practices of silviculture (reduced environmental weed-induced stress) to achieve expressive gains on ΔB and LUE. When managed traditionally, trees at wider layout cannot occupy the site satisfactorily to the point of suppress colonization of weeds and consequently avoid competition for resources. Denser plantations intensively managed, despite no competition with weeds, show competition among trees due to higher LAI, and high demand for water during the dry season, reducing the LUE (Fig. 5).

Intensive silviculture, with high rates of fertilization and weed control, are widely applied on forest plantations for cellulose and wood production (Gonçalves et al., 2004; Stape et al., 2004), increasing aboveground net primary production from 20% to 90% (Giardina et al., 2003; Stape et al., 2006).

On the opposite, silvicultural practices applied on native forest plantations aiming restoration of degraded lands receives usually low level of investment (Carpenter et al., 2004; Souza and Batista, 2004; Sampaio et al., 2007), due to the lack of a tangible commodity and an infinite growth period. Poor weed control, on dominated C_4 grass pastures, and none or low fertilization rates are not able to reduce environmental stress satisfactorily, resulting on high rates of mortality and ineffectiveness (Engel and Parrotta, 2001; Doust et al., 2008). Therefore, we tried to transfer the silvicultural technology of *Eucalyptus* wood production plantations to restoration plantations, reducing stress caused by weed competition and impoverished soils.

Our results strongly refute the preconception that fertilizing native trees planted for restoration would be a waste of money and resources (Carpenter et al., 2004). Stemwood productivity under intensive management was considerably higher since first year (2-folds), reaching almost 5-fold at third year (Fig. 2). The expressive gain in ΔB was a consequence of improved canopy structural and nutritional characteristics, with 3.7-fold more APAR (higher LAI) and 2.5-fold more canopy nitrogen, resulting in a 29% increase of the efficiency of converting APAR into stemwood biomass (Table 2). For commercial plantations, several studies obtained increase on productivity, improvements on canopy characteristics and enhance on efficiency of conversion PAR into biomass, with intensification of silvicultural management and alleviation of environmental stress (Beadle, 1997; Loik and Holl, 1999; Stape et al., 2008), and it seems that restoration forestry can use such concepts to increase the long-term success of recovering degraded areas.

According to the fertilization rates used, up to the second year, both traditional and intensive treatments received similar amounts of nutrients. Therefore, the 4.4-fold gain in ΔB induced by the intensive management at this age can be credited exclusively to the control of C_4 grasses, and must be visualized as a required practice (Lugo et al., 1990; Parrotta et al., 1997; Souza and Batista, 2004). Nevertheless, after the second year, the intensive silviculture effect is confounded between weed control and fertilization. Fertilization is need for satisfactory development of forest restoration plantations (Florentine and Westbrooke, 2004), especially on highly degraded and depleted soils (Funk and Vitousek, 2007).

The great responsiveness of these selected 20 species to intensive silviculture management (Fig. 6), open a new opportunity for the development of successful long-term restoration strategies for native species (Parrotta and Knowles, 2001). Indeed, as a consequence of this study, a parallel study using 120 Atlantic Forest species under intensive management, in the same Research Station, was installed in 2007 in order to provide an adequate restoration responsiveness classification for the Atlantic Forest species (Stape, 2008).

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