Restoration of Tropical Moist Forests on Bauxite-Mined Lands in the Brazilian Amazon

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Abstract

We evaluated forest structure and composition in 9- to 13-year-old stands established on a bauxite-mined site at Trombetas (Pará), Brazil, using four different reforestation techniques following initial site preparation and topsoil replacement. These techniques included reliance on natural forest regeneration, mixed commercial species plantings of mostly exotic timber trees, direct seeding with mostly native early successional tree species, and mixed native species plantings of more than 70 tree species (the current operational restoration treatment at this site). Replicated fixed-radius plots in each treatment and in undisturbed primary forest were used to quantify the canopy and understory structure and the abundance and diversity of all vascular plant species. Treatment comparisons considered regeneration density, species richness and diversity for all floristic categories, and, for trees and shrubs, the relative contribution of initial planting and subsequent regeneration from soil seed banks and seed inputs from nearby primary forests. With the possible exception of the stands of mixed commercial species, which were superior to all others in terms of tree basal-area development but relatively poor in species richness, all treatments were structurally and floristically diverse, with a high probability of long-term restoration success. Of these, the mixed native species plantings appeared to be at least risk of arrested succession due to the dominance of a broader range of tree species of different successional stages or expected life spans. In all treatments, several locally important families of primary forest trees (Annonaceae, Chrysobalanaceae, Lauraceae, Palmae and Sapotaceae) were markedly underrepresented due to a combination of poor survival of initial plantings and limitations on seed dispersal from the surrounding primary forest.

Introduction

Opencast mining for bauxite, cassiterite, iron, manganese, and kaolin has resulted since the 1960s in the annual loss of an estimated 2000–3000 ha of tropical forest in Brazil. While these mining activities directly affect relatively small forest areas compared to forest clearance for agriculture and unsustainable logging, their off-site environmental impacts can be extensive due to erosion and runoff resulting in siltation and deterioration of water quality in nearby rivers, lakes, and reservoirs.

To mitigate these adverse environmental impacts, effective forest restoration techniques are required. Their successful implementation requires careful planning and the integration of mining and rehabilitation operations based on sound silvicultural and ecological knowledge and principles (Bradshaw 1987). Proper site preparation, including minesite landscaping, topsoil handling and application, and deep-ripping of compacted subsoil, has been shown to be an essential prerequisite for good growth of planted tree species and vigorous natural regeneration of species from viable seeds contained in forest topsoil (Tacey 1979; Tacey & Glossop 1980; Fox 1984; Ferraz 1993; Grant et al. 1996; Parrotta et al. 1997). In addition, silvicultural knowledge is required to select species and establishment techniques appropriate to local site conditions and long-range restoration objectives. In many tropical regions, including the Amazon basin, restorationists lack basic, essential information on seed availability, propagation techniques, growth rates, and site adaptability for the hundreds of candidate tree species present in the natural forests (Knowles & Parrotta 1995).

Forest restoration programs operated by mining companies in Brazil (Majer 1992, 1996; Gaunt & Bliss 1993; Knowles & Parrotta 1995), Australia (Tacey 1979), and other tropical countries have therefore usually relied on the artificial regeneration of either native or exotic forest species to rapidly establish tree cover on reclaimed minesites and thereby facilitate natural forest succession. In Brazil prior to the early 1980s, bauxite mine rehabilitation programs involved reforestation with fast-growing exotic and native species, such as *Eucalyptus* spp., *Bracatinga scabrella*, and Australian *Acacia* spp.

Since 1979, the Brazilian mining company Mineração Rio do Norte S.A. has developed a reforestation pro-

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gram aimed at restoring the primary forest cover destroyed at a rate of approximately 100 ha/year during bauxite ore extraction at Trombetas in western Pará State (Knowles & Parrotta 1995). The mixed native species reforestation approach, involving careful site preparation (including topsoil replacement) and planting mixed stands of 80–100 species of native forest species at a total cost of approximately $2500/ha, has been the standard reforestation technique used at the Trombetas mine since the mid-1980s. This more sophisticated reforestation approach has become the industry norm in response to Brazilian environmental legislation that now requires companies to restore, to the greatest extent feasible, the original vegetation destroyed during mining.

Given adequate site preparation, it would be tempting to both simplify planning and operations and minimize restoration program costs by relying solely on natural forest-successional processes. The extent to which one can rely on seed-bank germination (from applied topsoil) to establish species-rich forest cover is largely unknown, although studies of forest succession following natural disturbances and agricultural abandonment can provide some guidance and generally suggest that early successional tree species, such as *Bellucia, Byrsonima, Cecropia, Croton*, and *Vismia* in the central Amazon region of Brazil, need not be planted due to their abundance in the soil seed bank and adaptability to degraded site conditions (Uhl 1987; Uhl et al. 1988).

On reclaimed minesites in this region, however, there is no certainty that succession will proceed towards mature secondary forest stands as it would following less intense forest disturbances, such as natural gap formation or timber harvesting. While earlier studies reported no detectable soil chemical change associated with bauxite mining and rehabilitation treatments, apart from a slight elevation in surface soil pH (Ferraz 1993; Parrotta et al. 1997), natural forest recovery may nonetheless be impeded by soil compaction, decreased soil porosity and infiltration capacity, and the loss by erosion of at least part of the soil microbial, fungal, and invertebrate communities. Under these conditions, hardy early successional tree species may become established, but their expected senescence and mortality within 10–20 years could result in either arrested succession or canopy opening that would facilitate invasion by persistent, fire-prone grasses that are known to preclude or severely slow subsequent forest regeneration (Uhl & Jordan 1984; Uhl et al. 1988; Nepstad et al. 1991; Parrotta 1993; Aide et al. 1995; Parrotta et al. 1997). The same risk applies to artificially regenerated forests established with the typically short-lived, often exotic, species generally used in mineland rehabilitation programs. This process has been observed elsewhere at the Trombetas minesite in both single-species stands of *Eucalyptus* spp. and *Acacia mangium* and on natural regeneration sites from 10 to 15 years of age (J.A.P. & O.H.K., personal observation).

At the Trombetas minesite, a number of reforestation methods, in addition to the standard mixed native species planting technique, were tested on a smaller scale during the 1980s. These included establishment of mixed species plantations by direct seeding with mainly short-lived, native early successional trees; mixed plantings of mostly exotic species (*Eucalyptus* spp., *Acacia mangium*, and *Sclerolobium paniculatum*); and reliance on natural regeneration following standard site preparation and topsoil application. The presence of these developing forest stands of similar age (9–13 years) and established by different techniques provided an opportunity to evaluate their relative contributions to meeting the company's goal and legal requirement to restore the original primary forest. This study was therefore undertaken to compare the structure, floristic composition, successional status, and sustainability of these alternative treatments with reference to the undisturbed primary forests surrounding the minesite.

Methods

Study Location

The Trombetas bauxite mine, operated by Mineração Rio do Norte S.A., is located in the Saracá-Taquera National Forest on an upland mesa (Saracá plateau) at an elevation of 180 m, 65 km northwest of the town of Oriximiná and 30 km south of the Trombetas River in western Pará State, Brazil (1°40′S, 56°27′W, Fig. 1). The local climate is characterized as Am (tropical monsoonal) in the Köppen system and corresponds to the tropical moist forest life zone in the Holdridge system (Tosi & Velez-Rodríguez 1983). Mean annual rainfall at Porto Trombetas (1970–1993) is 2185 $\pm$ 64 (SE) mm, with distinctly dry (winter) and wet (summer) seasons. The mean maximum and minimum temperatures are, respectively, 34.6°C and 19.9°C. Soils on the Saracá plateau are acidic yellow clay latosols with a thin humus layer (Ferraz 1993). The regional vegetation is evergreen equatorial moist forest, within which the forests occupying the upland mesas and surrounding slopes contain emergent trees reaching 45 m in height (Knowles & Parrotta 1995, 1997).

Reforestation Treatments

The study areas were located on the eastern side of the Saracá plateau (Fig. 2) on sites mined between 1982 and 1986 and in as yet undisturbed primary forest (Fig. 3). For all treatments, the standard reclamation and site preparation sequence was followed (Fig. 3), which includes leveling of the clay overburden, replacement of

Figure 1. Location of the study area.

approximately 15 cm of topsoil and woody debris (stockpiled for up to six months prior to application), deep-ripping of lines to a depth of 90 cm (1 m between lines), and planting along alternate rip lines at a spacing of 2 × 2 m with seeds, stumped saplings, and/or potted seedlings, depending on species and treatment.

The natural regeneration treatment (Fig. 4) included four areas ranging in size from 0.3 ha to 1.0 ha that were not planted after site preparation in 1984, 1985, and 1987, in which subsequent forest regeneration was initiated through soil seed bank germination. The mixed commercial species treatment (Fig. 5), established in plantation blocks totaling 2.0 ha in 1987, included mixed stands of *Eucalyptus camaldulensis, E. citriodora, E. pellita, E. torreliana, E. urophylla, Acacia mangium*, and the native species *Sclerolobium paniculatum*. In the direct seeding treatment, 48 species of mostly short-lived native primary forest taxa were planted over a 17-ha area by direct seeding in 1986; this stand was mowed at a height of 40 cm in 1987 to stimulate sprouting. In the mixed native species treatment (Figs. 2 & 6), approximately 70 native tree species of different successional stages were planted in 1985 over a 100-ha area.

Forest Stand Structure and Floristics

Between 1995 and 1997, we evaluated stand structure, floristic composition, and forest floor development for all treatments and in undisturbed primary forests on the Saracá plateau using replicated circular plots 10 m in diameter (78.5 m^2) as the standard measuring unit. Due to stand-area differences among treatments, the total sampling area varied among treatments: 942 m^2 in the natural regeneration treatment; 628 m^2 in the mixed commercial species treatment; 1256 m^2 in the direct seeding treatment; 2512 m^2 in the mixed native species treatment; and 628 m^2 in the undisturbed primary forest.

Natural regeneration sample plots were located randomly within the four study sites comprising this treatment (n = 2–4 per site), located from 100 to 800 m from the forested edge of the plateau. Sample plots in the mixed commercial species treatment were also located randomly within the stands, which were situated approximately 800 m from the plateau edge and the surrounding primary forest. In both the direct seeding and mixed native species treatments, sample plots were established along transects running towards the interior of the Saracá plateau from the intact old-growth forest along the edge of the plateau. Plot centers were located at 0, 10, 20, 40, 100, 250, 500, and 725 m along two transects in the direct seeding stands and at 0, 10, 20, 40, 80, 160, 320, and 640 m along each of four transects in the mixed native species stands. Primary forest plots were located along two 100-m transects in undisturbed forest areas in the general vicinity of the restoration areas on the eastern side of the Saracá plateau, approximately 50 m from the plateau edge.

Within each of the 78.5-m^2 sample plots, we made a complete inventory of all trees and shrubs, vines, herbs, and grasses. For each of these floristic categories, we recorded the total numbers of individuals (or clumps, for grasses) of each species. For trees and shrubs (including palms), we also measured height and stem diameters (at 1.3 m diameter at breast height) for trees over 2 m in height. Data on height and stem diameter for planted trees occurring in each plot were recorded separately. Woody species were also classified by their expected longevity, or life span (<20, 20–40, 40–80, or >80 years), based on Knowles's long-term observations of the local tree flora.

Canopy closure was estimated as the mean percentage crown cover measured with a spherical crown densiometer at 1 m from ground level at four points located 3 m from plot centers (N, S, E, and W compass bearings). Litter and humus depths were measured at 10 randomly located points within each plot, with plot means for each horizon used for subsequent analyses.

Data Analysis

We calculated numbers of individuals per square meter and basal area (for trees ⩾2 m tall) for all species in each treatment. Species richness for each floristic category in each plot was expressed simply as the number of species, and species diversity was estimated by the Shannon-Wiener index (H'). Based on the total plant species list for all plots in each treatment, Sorensen's quotient of similarity (I) was calculated for each floristic category

Figure 3. The Saracá plateau before and after bauxite ore extraction. Upper: Undisturbed primary forest; note abundance of palms in understory, typical of these forests. Lower: Site preparation, showing overburden hills (background, left) and topsoil and woody debris to be spread on site prior to planting (foreground).

Figure 4. Ten-year-old natural regeneration (topsoil application only). Note stilt-rooted *Cecropia* stem and abundance of *Cecropia* leaf litter in foreground.

to assess the degree of similarity between restoration treatments and the undisturbed primary forest. Mean canopy closure, canopy height, tree basal area, litter and humus depth, plant density, species richness, and species diversity for woody species, vines, herbs, and grasses were compared among treatments with unpaired two-group *t* tests.

Results

Forest Structure

Forest canopy cover, tree basal area, and litter and humus depths were broadly similar among restoration treatments but distinctly dissimilar to those of the undisturbed primary forest (Table 1). Average crown cover ranged from 53% to 64% and tree basal area from 13.9 to 24.9 m^2/ha among restoration treatments, compared with 76% and 77 m^2/ha in the undisturbed primary forest. These values were highest in the mixed commercial species treatment and lowest in the mixed native species treatment. The proportion of total basal area comprised by planted trees was high in all plantation treatments: 93% in the mixed commercial species treatment, 84% in the direct seeding treatment, and 80% in the mixed native species treatment. Mean canopy height was significantly greater in the primary forest treatment (21.6 ± 1.5 SE m) and mixed commercial species treatment (17.4 ± 0.9 SE m) than in the other three treatments, with mean values ranging from 10.4 ± 0.4 SE m in the direct seeding treatment to 11.7 ± 0.4 SE m in the natural regeneration stands.

Average litter depths were significantly greater in the mixed commercial species and natural regeneration treatments (range of means: 43–46 mm) than in the direct seeding, mixed native species, and primary forest stands (range of means: 29–33 mm). Humus depths averaged from 5.7 ± 0.5 SE mm in the mixed commercial species stands to 8.3 ± 1.0 SE mm in the mixed native species stands, with no consistent differences among restoration treatments. These values were lower, though generally not significantly different, than those recorded in the primary forest (mean: 13.3 ± 3.3 SE mm).

The density of both planted and naturally regenerated woody species was slightly lower in all restoration

◄ Figure 2. Aerial view of the eastern side of the mined Saracá plateau, near Porto Trombetas, Pará, Brazil. Upper: Newly reforested areas in foreground and center of photo (1987); mine face (trench) to the right. Lower: Closer view of the same area in 1992 showing 6-year-old mixed native species plantings.

Figure 5. Ten-year-old mixed commercial species treatment, with overstory dominated by planted *Eucalyptus* spp., *Acacia mangium,* and *Sclerolobium paniculatum.* Note low density of woody understory regeneration relative to that in the mixed native species treatment (Fig. 6).

treatments (range of means: 1.55–3.47 individuals/m^2) than in the primary forest (mean: 5.47 ± 0.47 SE/m^2). Among restoration treatments, the direct seeding treatment had significantly higher population densities than both the natural regeneration and mixed commercial species treatments (Table 1). Planted trees comprised between 5.6% and 15.0% of the total among the plantation treatments, the remainder arising either from soil seedbank regeneration, subsequent seed inputs from surrounding primary forest areas, or, for a small number of species, regeneration from planted trees.

Seedlings (individuals $<$2 m tall) comprised between 77% and 87% of the total woody species density among restoration treatments and 92% in the primary forest. The average density of larger stems ($\geqslant$2 m tall) ranged from 0.28 to 0.54 individuals/m^2 among restoration treatments and was significantly higher in the direct seeding treatment (mean: 0.54 ± 0.03 SE/m^2) than in the other restoration treatments (range of means: 0.28–0.40/m^2) or the primary forest (mean: 0.43 ± 0.02/m^2).

The density of vines, grasses, and herbs differed significantly among treatments (Table 1). Vines were significantly more abundant in the direct seeding treatment (mean: 0.82 ± 0.10 SE individuals/m^2) than in the other treatments (range of means: 0.34–0.43 individuals/m^2) or the primary forest (mean: 0.48 ± 0.06 SE individuals/m^2). Grasses were most abundant in the direct seeding treatments (range of means: 1.14–1.16 clumps/m^2), intermediate in the mixed native species and natural regeneration treatments (range of means: 0.40–0.52 clumps and least abundant in the primary forest (mean: 0.17 ± 0.06 SE clumps/m^2). Herbs were significantly more abundant in the mixed commercial species stands (mean: 1.18 ± 0.35 SE individuals/m^2) than in all other treatments, which ranged from 0.019 ± 0.004 SE individuals/m^2 in the mixed commercial species stands to 0.18 ± 0.07 SE individuals/m^2 in the direct seeding treatment. The overall abundance of herbs was intermediate in the primary forest (mean: 0.36 ± 0.07 SE individuals/m^2).

Floristic Composition and Diversity

Tree species richness varied greatly among treatments (Table 2). The total numbers of woody species recorded were 86 in the natural regeneration treatment (representing 32 families); 40 in the mixed commercial species treatment (from 21 families); 117 in the direct seeding treatment (from 37 families); 141 in the mixed native species treatment (from 38 families), and 157 in the primary forest (from 39 families). The numbers of planted tree species differed among treatments: seven in the mixed commercial species treatment, 42 in the direct seeding treatment, and 73 in the mixed native species treatment.

Differences in total tree species richness among treatments were partly an artifact of differences in treatment sampling area. The species-area relationships (Fig. 7) clearly show that, for most treatments, total sampling area was insufficient to capture the total tree flora in these forest stands, although the shapes of these curves indicate that our surveys included at least 90% of the projected total numbers of species. Also, the number of planted species differed among treatments; if planted species were discounted, species area curves would appear similar for all but the mixed commercial species stands, which contained a smaller number of tree and shrub species than the other treatments.

With the exception of the mixed commercial species treatment, the restoration treatments contained between 55% and 90% of the total number of species and 82% to 97% of the total number of families found in the primary forest plots. The restoration treatments exhib-

Table 1.
Structural characteristics of 9- to 13-year-old reforestation plots and primary forest at the

	Treatment				
	Natural Regeneration	*Mixed Commercial Species*	*Direct Seeding*	*Mixed Native Species*	*Undisturbed Primary Forest*
Year established	1983–1987	1987	1986	1985	
Years since establishment	9–13	9	10	10	
Sample area (m^2)	942	628	1256	2512	628
No. of sample plots/treatment, *n*	12	8	16	32	8
Crown cover (%)	63.5^{b}	59.8^{bc}	53.2^{cd}	56.1^{cd}	75.7^{a}
Canopy height (m)[2]	11.7^{b}	17.4^{a}	10.4^{b}	10.6^{b}	21.6^{a}
Tree basal area (m^2/ha)	19.6^{cd}	24.9^{b}	16.8^{de}	13.9^{e}	76.5^{a}
Litter depth (mm)	46.0^{a}	42.7^{a}	32.7^{b}	32.4^{b}	29.4^{b}
Humus depth (mm)	6.3^{ab}	5.7^{b}	6.9^{ab}	8.3^{ab}	13.3^{a}
Density (no. of individuals/m^2)					
Woody species (all)	1.55^{cd}	1.32^{d}	3.47^{b}	3.06^{bc}	5.47^{a}
Planted	0	0.15^{b}	0.52^{a}	0.18^{b}	0
Other[3]	1.55^{cd}	1.17^{d}	3.04^{b}	2.88^{bc}	5.47^{a}
Woody species, <2 m tall	1.19^{cd}	1.04^{d}	2.93^{b}	2.66^{bc}	5.04^{a}
Woody species, >2 m tall	0.36^{b}	0.28^{b}	0.54^{a}	0.40^{b}	0.43^{b}
Vines	0.43^{b}	0.34^{b}	0.82^{a}	0.40^{b}	0.48^{b}
Grasses	0.52^{bc}	1.16^{a}	1.14^{ab}	0.40^{c}	0.17^{d}
Herbs	0.025^{c}	1.18^{a}	0.18^{b}	0.019^{c}	0.36^{b}

[1]Similar superscript letters within a row indicate that means were not significantly different between treatments ($p < 0.05$, *t* test).
[2]Calculated as mean of plot averages for five tallest trees per plot.
[3]"Other" species include those regenerating from the seed bank in applied soil or arising from seed inputs from surrounding primary forests.

ited a low to moderate degree of floristic similarity to the original primary forest, as measured by Sorensen's quotient of similarity (*I*). These values ranged from a low of 0.16 in the mixed commercial species treatment to 0.50–0.51 in the direct seeding and mixed native species treatments, with an intermediate value (0.40) for the natural regeneration treatment (Table 3). Although most of the families present in the primary forest tree flora were represented in the natural regeneration, direct seeding, and mixed native species treatments, certain important families (Annonaceae, Chrysobalanaceae, Lauraceae, Palmae, Sapotaceae) were, in general, poorly represented in all restoration treatments.

Discounting tree seedlings (individuals <2 m tall), total tree species richness varied considerably among treatments and between restoration treatments and the primary forest. The primary forest plots contained a total of 88 tree species with individuals over 2 m in height, compared with 19 species in the mixed commercial species treatment, 37 species in the natural regeneration treatment, 27 species in the direct seeding treatment, and 73 species in the mixed native species treatment.

These general trends are supported by analyses of plot-based (equal area) measurements of species richness (Table 3). The average numbers of tree and shrub species per plot were significantly different among all treatments and increased two-fold from the mixed commercial species treatment (mean: 17.5 ± 0.7 SE) to the direct seeding treatment (mean: 35.4 ± 1.9 SE), with intermediate values in the natural regeneration treatment (mean: 23.1 ± 1.7 SE) and mixed native species treatment (mean: 28.5 ± 1.3 SE). In the primary forest, mean tree and shrub species richness was 67.3 ± 3.0 SE species/plot. Planted species comprised up to one-third of the total in the mixed commercial species (31.4%), direct seeding (32.8%), and mixed native species (30.9%) treatments. Tree seedling and sapling (individuals <2 m tall) species richness was significantly different among all restoration treatments and ranged from an average of 9.8 ± 1.0 SE species/plot in the mixed commercial species treatment to 31.6 ± 2.0 SE species/plot in the direct seeding treatment. The primary forest plots had a significantly larger number of species in this size class (mean: 59.8 ± 2.6 SE species/plot) than all restoration treatments. Woody species richness for larger individuals (⩾2 m tall) was very similar among restoration treatments (range of means: 11.4–14.6 species/plot) but significantly lower than in the primary forest (mean: 21.5 ± 1.9 SE species/plot).

Average woody species diversity, as measured by the Shannon-Wiener index (H'), varied among restoration treatments from 0.92 ± 0.04 SE (mixed commercial species treatment) to 1.20 ± 0.14 SE (natural regeneration treatment), compared to 1.35 ± 0.06 SE in the primary forest (Table 3). Mean H' values were significantly

Figure 6. Mixed native species plantings. Upper: 1.5-year-old stands. Note rapid early growth of large-leaved *Cecropia* and other pioneer species germinated from applied soil seedbank. Lower: Eleven-year-old stand. Each 78.5-m^2 plot in this treatment contained an average of 28 native tree species, of which more than half were represented by individuals over 2 m tall. Photo taken approximately 50 m from plateau (primary forest) edge, pictured in foreground of Fig. 2 (upper photo).

Table 2. Number of tree and shrub species surveyed in 9- to 13-year-old reforestation plots and undisturbed primary forest on the Saracá plateau at the Trombetas bauxite-mined site.*

Family	*Natural Regeneration*	*Mixed Commercial Species*	*Direct Seeding*	*Mixed Native Species*	*Undisturbed Primary Forest*
Anacardiaceae	3		2	3	4
Annonaceae	5	3	3	7	10
Apocynaceae	3	1	2	6	4
Araliaceae		1	1	1	
Bignoniaceae	2	1	3	3	1
Boraginaceae			1	1	1
Burseraceae	3		4	4	4
Celestraceae	1	1	1	1	
Chrysobalanaceae	2		2	3	10
Clusiaceae	1	1	1	1	1
Combretaceae			2	1	1
Connaraceae					2
Ebenaceae	1		1	1	1
Elaeocarpaceae			1		1
Euphorbiaceae	3		4	5	4
Flacourtiaceae	1	1	3	2	2
Guttiferae	3	2	3	3	2
Humiriaceae	4	3	2	4	4
Lauraceae	4	1	5	6	13
Lecythidaceae			3	2	3
Leguminosae (C)	5	1	5	10	7
Leguminosae (M)	12	4	23	20	11
Leguminosae (P)	3		5	12	3
Malpighiaceae	1	1	1	2	1
Melastomataceae	4	5	6	6	3
Meliaceae			1	1	3
Monimiaceae	1			1	1
Moraceae	4	2	8	7	9
Myristicaceae			2	2	3
Myrtaceae	1	5	4	2	3
Olacaceae				1	1
Palmae	5	2	4	4	10
Proteaceae					1
Rubiaceae	3	2	3	5	4
Rutaceae	2				
Sapindaceae	1				2
Sapotaceae			3	2	14
Simarubaceae	1		1	1	1
Sterculiaceae			1	1	1
Tiliaceae	1	1		2	
Ulmaceae	1	1			
Verbenaceae	1		1		
Violaceae	1		2	2	3
Vochysiaceae			1		1
Unidentified	3	1	2	6	7
Total no. families	32	21	37	38	39
Total no. species	86	40	117	141	157

*Sampling areas differed among treatments: 628 m^2 for mixed commercial species treatment and primary forest, 942 m^2 for natural regeneration treatment, 1256 m^2 for direct seeding treatment, and 2512 m^2 for mixed native species treatment.

higher for the primary forest plots than for all restoration treatments except the natural regeneration treatment.

Species richness for vines averaged 5.3–7.4 species/plot among treatments and was significantly lower in the mixed native species treatment than in the direct seeding treatment (Table 3). With the exception of the direct seeding treatment, mean vine species richness was significantly lower in the restoration treatment plots than in those of the primary forest (mean: 9.9 ± 0.7 species/plot). Vine species diversity (H') values were not significantly different among restoration treatments (range of means: 0.49–0.58), though all were significantly less than the mean for the primary forest

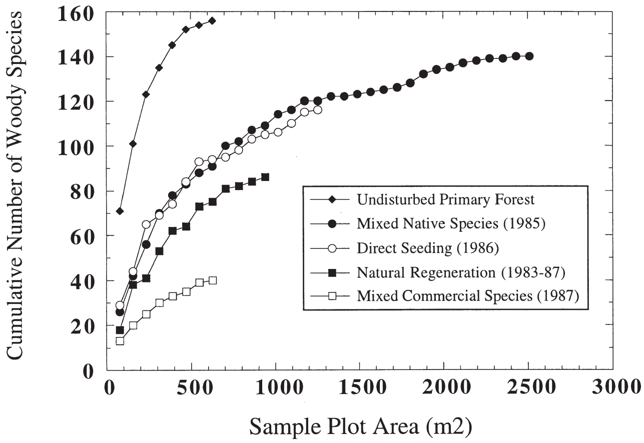

Figure 7. Species-area relationships for tree and shrub species in restoration treatments and undisturbed primary forest.

plots (0.81 ± 0.06 SE). The vine flora in the restoration treatments exhibited a moderate degree of floristic similarity (I) to that of the original primary forest, with values ranging from a low of 0.37 in the mixed commercial species treatment to 0.63–0.68 in the direct seeding, mixed native species treatment, and natural regeneration treatment.

In the primary forest there were significantly fewer grass species (mean: 0.6 ± 0.2 SE grass species) and more herb species (mean: 3.1 ± 0.2 SE herb species/plot) than in all restoration treatments (range of means: 2.3–54.4 grass species/plot; 0.7–1.9 herb species/plot). Average species richness for both grasses and herbs was significantly higher in the mixed commercial species and direct seeding treatments than in the mixed native species treatment. Grass species diversity (H') was highest in the direct seeding and mixed commercial species treatments (range of means: 0.37–0.39), intermediate in the other restoration treatments (range of means: 0.21–0.26), and lowest in the primary forest (mean: 0). Herb diversity (H') was significantly higher in the primary forest (mean: 0.34 ± 0.4) than in all restoration treatment plots (range of means: 0.04–0.13). The degree of floristic similarity between the restoration treatments and primary forest was generally low for herbs and grasses, particularly so in the mixed commercial species treatment ($I = 0$ for both floristic groups). In the remaining restoration treatments, mean I values for herbs were lower in the direct seeding and natural regeneration treatments (0.40–0.44) than in the mixed native species treatment.

Tree Species Dominance and Longevity

There were marked differences among treatments in tree species dominance, as measured by relative basal

Table 3. Species richness and diversity in 9- to 13-year-old reforestation plots and primary forest at the Trombetas bauxite-mined site.[1]

	Treatment				
	Natural Regeneration	*Mixed Commercial Species*	*Direct Seeding*	*Mixed Native Species*	*Undisturbed Primary Forest*
Species richness (no. of species/plot)					
Woody species (all)	23.1^{d}	17.5^{e}	35.4^{b}	28.5^{c}	67.3^{a}
Planted	0	5.5^{b}	11.6^{a}	8.8^{a}	0
Other[2]	23.1^{b}	12.3^{c}	28.6^{b}	23.7^{b}	67.3^{a}
Woody species, <2 m tall	16.0^{d}	9.8^{e}	31.6^{b}	21.2^{c}	59.8^{a}
Woody species, >2 m tall	11.4^{c}	11.4^{c}	11.6^{c}	14.6^{b}	21.5^{a}
Vines	$6.1b^{c}$	5.6^{bc}	7.4^{ab}	5.3^{c}	9.9^{a}
Grasses	2.3^{ab}	4.0^{a}	4.0^{a}	2.6^{b}	0.6^{c}
Herbs	1.1^{bc}	1.9^{b}	1.6^{b}	0.7^{c}	3.1^{a}
Species diversity (Shannon-Wiener index: H')					
Woody species	1.20^{abc}	0.92^{cd}	1.17^{b}	0.93^{d}	1.35^{a}
Vines	0.55^{b}	0.49^{b}	0.58^{b}	0.52^{b}	0.81^{a}
Grasses	0.21^{b}	0.37^{ab}	0.39^{a}	0.26^{b}	0^{c}
Herbs	0.11^{b}	0.04^{b}	0.13^{b}	0.04^{b}	0.34^{a}
Sorensen's Index of Similarity (I)[3]					
Woody species	0.40	0.16	0.50	0.51	1.00
Vines	0.68	0.37	0.63	0.67	1.00
Grasses	0.25	0	0.18	0.20	1.00
Herbs	0.44	0	0.40	0.55	1.00

[1]Similar superscript letters within a row indicate that means were not significantly different between treatments ($p < 0.05$, t test).
[2]"Other" species include those regenerating from the seed bank in applied soil or arising from seed inputs from surrounding primary forests.
[3]Comparisons with undisturbed primary forest. Complete plant lists from primary forest and restoration treatments are available from the authors.

areas (Table 4). In the natural regeneration treatment, the pioneer species *Cecropia* sp., *Byrsonima* sp., *Vismia guianesis, Conceveiba* sp., and *Bellucia dichotoma* together comprised 62% of the total basal area. In the mixed commercial species treatment, the planted species *Eucalyptus pellita, E. urophylla, Sclerolobium paniculatum*, and *Acacia mangium* comprised 80% of the total basal area. In the direct seeding treatment, the dominant species was *Sclerolobium paniculatum*, with 54% of the total basal area. In the mixed native species treatment, 10 species—*Croton* sp., *Joannesia princips, Belucia dichotoma, Parkia gigantocarpa, Byrsonima* sp., three *Vismia* spp., and *Tatapira guianensis*—comprised 64% of the total basal area. The primary forest plots were dominated by a very different suite of tree species, with 75% of the total basal area represented by species either rare or absent from the restoration plots, including *Brosimum rubescens, Astrocaryum murumuru* and other palms, *Endopleura uchi, Virola* sp., and *Nectandra rosa*, which collectively comprised 57% of the total. Among restoration treatments, the mixed native species plots more closely resembled the primary forest in that they exhibited much less marked patterns of dominance by fewer tree species than the other restoration treatments.

When tree species are categorized by their expected average life spans, differences among treatments are

Table 4. Tree species comprising 75% of total stand basal area in 9- to 13-year-old restoration treatments and undisturbed primary forest at the Trombetas bauxite-mined site.

Treatment	*Dominant Tree Species*	*Family*	*Basal Area (%)*	*Longevity (years)*
Natural regeneration	*Cecropia* sp.	Moraceae	29.6	<20
	Byrsonima sp.	Malpighiaceae	12.6	20–40
	Vismia guianensis	Guttiferae	7.7	<20
	Conceveiba sp.	Euphorbiaceae	6.3	<20
	Bellucia dichotoma	Melastomataceae	5.4	<20
	Laetia procera	Flacourtiaceae	4.4	40–80
	Trattinickia burserifolia	Burseraceae	4.2	40–80
	Duguetia riparia	Annonaceae	3.9	<20
	28 other species		25.9	
Mixed commercial species	*Eucalyptus pellita*	Myrtaceae	22.6	20–40
	Sclerolobium paniculatum	Leguminosae (C)	21.4	<20
	Acacia mangium	Leguminosae (M)	20.2	<20
	Eucalyptus urophylla	Myrtacea	15.9	20–40
	15 other species		19.9	
Direct seeding	*Sclerolobium paniculatum*	Leguminosae (C)	53.9	<20
	Cassia sp.	Leguminosae (C)	12.3	<20
	Cassia leiandra	Leguminosae (C)	5.1	20–40
	Bellucia dichotoma	Melastomataceae	4.9	<20
	38 other species		23.8	
Mixed native species	*Croton* sp.	Euphorbiaceae	12.9	<20
	Joannesia princips	Euphorbiaceae	10.8	20–40
	Bellucia dichotoma	Melastomataceae	8.7	<20
	Parkia gigantocarpa	Leguminosae (M)	8.6	40–80
	Byrsonima sp.	Malpighiaceae	8.4	20–40
	Vismia spp. (3)	Guttiferae	8.1	<20
	Tatapira guianensis	Anacardiaceae	6.3	20–40
	Unidentified ("pau de rego")	Unknown	2.8	<20
	Parkia oppositifolia	Leguminosae (M)	2.7	20–40
	Hymenaea sp.	Leguminosae (C)	2.6	>80
	Unidentified ("tapioca")	Unknown	2.5	<20
	60 other species		25.6	
Undisturbed primary forest	*Brosimum rubescens*	Moraceae	14.3	>80
	Astrocaryum murumuru	Palmae	11.4	20–40
	Unidentified	Palmae	10.6	20–40
	Endopleura uchi	Humiriaceae	8.9	40–80
	Virola sp.	Myristicaceae	5.9	40–80
	Nectandra rosa	Lauraceae	5.5	>80
	Unidentified	Rubiaceae	4.4	20–40
	Dialium guianensis	Leguminosae (C)	4.4	>80
	Duroia sp.	Rubiaceae	3.7	40–80
	Eschweilera odora	Lecythidaceae	3.4	40–80
	Croton sp.	Euphorbiaceae	3.3	<20
	145 other species		24.2	

apparent (Table 5). For all treatments, the proportions of species and total basal area decreased from younger to older tree life-span classes, in contrast to the primary forest, where very short-lived species (<20 years) were less numerous than longer-lived species (20–40 years or 40–80 years). The percentage of species with expected life spans over 40 years was lowest in the mixed commercial species treatment (23%), intermediate in the natural regeneration treatment (35%), and highest in the direct seeding and mixed native species treatments (43%). In the primary forest, such longer-lived species comprised 44% of the total.

Treatment differences in basal area distributions followed similar but more pronounced trends. In the mixed commercial species, tree species with expected life spans over 40 years comprised 0.5% of total basal area. The direct seeding treatment was also dominated by short-lived trees, with 88% of the total basal area comprised of species with life spans below 20 years and only 2.6% comprised of trees with life spans over 40 years. The natural regeneration treatment was also dominated by short-lived species, though longer-lived (>40 years) taxa contributed significantly to total basal area (21%). The most even life-span distribution of tree species and total basal area was found in the mixed native species treatment. In these stands, very short-lived (<20 years) tree species comprised 45% of the total basal area, and long-lived species (>40 years) 23% of total basal area. In the primary forest, very short-lived trees comprised only 6.1% of the total basal area; the remaining basal area was distributed among species with expected life spans of 20–40 years (37%), 40–80 years (33%), and >80 years (24%).

Discussion

All of the restoration techniques examined in this study were effective in rapidly reestablishing forest cover at this site. The most productive treatment in terms of basal area development and height growth was the mixed commercial species treatment, followed by the natural regeneration, direct seeding, and mixed native species treatments. Tree basal areas in the restoration treatments ranged from 18% (in the mixed native species plots) to 33% (in the mixed commercial species plots) of that in the primary forest plots.

An inverse relationship was observed between litter accumulation and humus depth among treatments. Litter depths were greatest in the natural regeneration treatment, followed by the mixed commercial species, direct seeding, and mixed native species treatments, and lowest in the primary forest. Humus depths, in contrast, were greatest in the primary forest, followed by the mixed native species, direct seeding, natural regeneration, and mixed commercial species treatments. Field observations indicate that the higher litter accumulation and slower humus-layer formation in the natural regeneration and mixed native species plots are due to the relatively slow decomposition of the dominant species in these stands (compared to other treatments): *Cecropia* spp., in the natural regeneration treatment and *Eucalyptus* spp. and *Acacia mangium* in the mixed commercial species treatment. These trends may reflect treatment differences in the development and activity of litter invertebrate communities and other litter decomposers, a topic meriting further research.

Apart from the mixed commercial species treatment, overall trends in species richness indicate that the floristic composition of these treatments is generally developing, at different rates, towards that of the primary forest on the Saracá plateau prior to mining. But analyses of basal-area dominance among restoration treatments clearly show that it will take at least several decades before the species that presently dominate the primary forest, though often present in the understory of the restoration stands, will assume a significant structural role.

Table 5. Expected longevity of planted and naturally regenerating tree and shrub species in 9- to 13-year-old reforestation and primary forest plots at the Trombetas bauxite-mined site (figures indicate average values for each treatment).

	Treatment				
	Natural Regeneration	*Mixed Commercial Species*	*Direct Seeding*	*Standard Reforestation*	*Primary Forest*
Percentage of species					
life span <20 years	40.7	40.0	36.7	31.9	24.1
life span 20–40 years	24.4	37.5	20.5	25.5	31.9
life span 40–80 years	23.3	17.5	24.8	27.0	31.9
life span >80 years	11.6	5.0	18.0	15.6	12.1
Percentage of total basal area					
life span <20 years	64.6	46.7	88.4	44.5	6.1
life span 20–40 years	14.8	52.8	9.1	32.5	37.0
life span 40–80 years	12.3	0.5	1.3	14.9	33.0
life span >80 years	8.4	0.0	1.3	8.2	23.9

The range of values recorded in this study for stand basal area, canopy height, tree density, and tree species richness are very similar to those reported for similar-aged secondary forests on former slash-and-burn sites in this region. For example, in 8-year-old secondary forests near Paragominas in eastern Pará arising after forest clearance, burning, (unsuccessful) seeding with pasture grasses, and subsequent abandonment, Uhl et al. (1988) reported that stand basal area ranged from 15.9 to 21.4 m^2/ha and canopy height from 11 to 14 m. In their study, the overall density of trees and tree seedlings was 1.71–2.53 individuals/m^2, or 1.00–2.05 individuals/m^2 for seedlings and saplings under 2 m tall and 0.48–0.71 individuals/m^2 for trees at or above 2 m tall. These values generally lie within the range of those recorded in our study in the natural regeneration, direct seeding, and mixed native species treatments in somewhat older stands (9–13 years old). With regard to tree species richness, which ranged from 17.5 to 35.4 species per plot (78.5 m^2) among treatments in the present study, Uhl et al. (1988) reported a somewhat lower range of 21.0 to 24.8 tree species per 100 m^2 in the 8-year-old secondary forest stands near Paragominas. Given the more severe vegetation and soil disturbances associated with the mining process at Trombetas, it is encouraging to note the structural similarities between the various reforestation treatments at 9–13 years old and 8-year-old secondary forest stands on abandoned slash-and-burn sites subjected to minimal use or management.

The results of this study reveal a number of differences among treatments that affect their long-term value for forest restoration at this site. The mixed commercial species treatment, dominated by *Eucalyptus* spp., *Sclerolobium paniculatum*, and *Acacia mangium*, stands out clearly at the most productive as indicated by data on basal area and tree height growth. The abundance, mean height, and species richness of trees and shrubs regenerating in the understory were significantly lower, however, than in either the direct seeding or mixed native species treatments. The relatively low regeneration density in this treatment is most likely due in part to the rapid growth rates of the planted trees, to relatively high understory light levels, and to increased grass and herb densities, all of which result in increased root competition among germinating woody species. The significantly lower understory species richness in these stands relative to that of the other restoration treatments also suggests possible limitations on seedbank germination and/or seed inputs by birds, bats, and other mammals that are the main agents of seed dispersal from the primary forest. As a result, the floristic composition of the woody flora in this treatment was the least similar of the four treatments studied to that of the primary forest on the Saracá plateau. The overwhelming dominance of short-lived species (<20 and 20–40 years) in this treatment, based on percentages of species and total basal area, places these stands at greatest potential risk of early canopy senescence. Without a tall, dense, species-rich woody understory, these stands could, in the event of overstory mortality, become dominated by grasses and very short-lived pioneer trees and shrubs, as has been observed elsewhere at the minesite in 10 to 15-year-old *Eucalyptus* spp. and *Acacia mangium* plantations (J.A.P. & O.H.K., personal observation).

Among the other treatments we studied, differences affecting their biodiversity restoration value are less marked. The direct seeding treatment, with its overstory dominated by *Sclerolobium paniculatum*, ranked very high in stand basal area and in abundance and species richness for planted trees and understory regeneration in both the smaller (<2 m) and larger (⩾2 m) height classes. Despite these highly favorable characteristics, the direct seeding treatment has two notable disadvantages. The principal structural weakness of these stands is the dominance of their basal area by very short-lived (<20 years) species, particularly *Sclerolobium paniculatum*, which comprises more than 50% of the total stand basal area. A second, apparently related, factor is the density of grasses, which were, as in the mixed commercial species treatment, two to three times more abundant than in the mixed native species and natural regeneration treatments. High understory grass density in this treatment appears inconsistent with high seedling density and may be a recent development, as the canopy of these stands is beginning to open, allowing more light to penetrate to the forest floor and thus facilitating the establishment of grasses. If in fact the *Sclerolobium*-dominated canopy is senescing and favoring understory grasses, it remains to be seen if the longer-lived species now established in the understory, mostly in the smaller size classes (<2 m tall), will successfully compete and ultimately suppress these grasses or if the grasses will become more abundant and slow forest succession.

Considering the remaining treatments, both the natural regeneration and mixed native species stands are developing towards late secondary native forest, although this process appears more advanced in the latter treatment. While crown cover and tree basal area are significantly greater in the natural regeneration treatment, woody species abundance (both size classes) and species richness are significantly greater in the mixed native species treatment. Further, the natural regeneration treatment overstory is dominated by short-lived, pioneer tree species (such as *Cecropia, Vismia, Byrsonima* spp.) to a far greater extent than in the mixed native species treatment, as was the case in the mixed commercial species and direct seeding treatments. Although the low grass density in the natural regeneration stands does not indicate overstory gap formation, the low density of woody seedlings and larger stems in this treatment raises some doubt as to whether there would be sufficient woody species cover to suppress grasses when the dominant *Cecropia* and other pioneer species senesce in the near future. Potential restoration setbacks related to early overstory mortality and arrested succession would therefore appear least likely in the mixed native species treatment.

These results indicate that the current reforestation approach of the Mineração Rio do Norte S.A.—mixed native species planting—is yielding favorable results in that the restoration process appears to be self-sustaining. These findings run contrary to the assumptions of some restorationists that high-diversity forest systems cannot be successfully established through high-diversity planting schemes (Dobson et al. 1997). But several of the most important families, in terms of dominance and ecological function, in the primary forest are presently either rare or absent from all restoration treatments (i.e., Annonaceae, Chrysobalanaceae, Lauraceae, Palmae and Sapotaceae). Tree species from these families generally performed poorly when planted under open conditions in the mixed native species areas and generally produced larger than average seeds requiring more specialized seed dispersers for their transport from the primary forest (Parrotta et al. 1997). Assuming that the restoration treatment stands continue to develop both structurally and floristically, which appears more likely in the case of the extensive mixed native species areas than in the other (smaller-scale) treatments, species from these presently underrepresented families may eventually become established as conditions become more favorable for a greater diversity of seed-dispersing birds and mammals, and for seed germination and seedling growth. Nonetheless, restoration managers at this site should carry out understory enrichment plantings of these generally shade-demanding species when the planted trees are sufficiently tall to permit easy access, usually about 5 years after planting.

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