ELSEVIER

Ecological Engineering 17 (2001) 219–239

ECOLOGICAL ENGINEERING

www.elsevier.com/locate/ecoleng

# Restoring tropical forests on lands mined for bauxite: Examples from the Brazilian Amazon

John A. Parrotta [a,*], Oliver H. Knowles [b]

[a] *International Institute of Tropical Forestry, USDA Forest Service, P.O. Box 25000, Río Piedras, PR 00928-5000, USA*
[b] *C.P. 15, Santarém, 68005.970 Pará, Brazil*

Accepted 19 August 2000

**Abstract**

Restoring self-sustaining tropical forest ecosystems on surface mined sites is a formidable challenge that requires the integration of proven reclamation techniques and reforestation strategies appropriate to specific site conditions, including landscape biodiversity patterns. Restorationists working in most tropical settings are usually hampered by lack of basic information on the wide variety of native tree species that characterize the pre-disturbance forests, as well as insufficient understanding of the ecology of disturbance and natural recovery to design effective restoration programs. A notable exception to this is the forest restoration program developed since the early 1980s by a Brazilian bauxite mining company operating at Trombetas in Pará State in central Amazonia. A systematic nursery and field research strategy was used to develop a reforestation program based on mixed plantings of more than 70 native old-growth forest tree species. This technique has been used to replant about 100 ha of deforested minelands each year over the past 15 years. Research in recent years has evaluated this approach and other, generally simpler, reforestation methods used at a smaller scale at this site. Post-plantation biodiversity development and other indicators of restoration success or sustainability were recorded. The results of these studies have shown the overwhelming importance of careful site preparation and topsoil handling/replacement practices in determining both future productivity and biodiversity of the redeveloping forests, irrespective of the complexity of the planting design used. The inclusion of a wide variety of forest species, particularly later successional species, was very important for long-range restoration owing to limitations on natural recovery processes that inhibit seed dispersal and subsequent colonization of many old-growth forest species. Many of the lessons learned at this site are applicable to improve the design of mineland rehabilitation and forest restoration programs worldwide. 

*Keywords:* Bauxite mine rehabilitation; Brazil; Natural regeneration; Plantations; Restoration; Soil seed bank; Succession; Tree life spans; Tropical forests

## 1. Introduction

Surface mining in most tropical countries directly affects relatively small areas of forest com-

* Corresponding author. Tel.: +1-787-7665335; Fax: +1-787-7666263.
*E-mail address:* jparrotta@fs.fed.us (J.A. Parrotta).

0925-8574/01/$ - see front matter 
PII: S0925-8574(00)00141-5

pared with forest cleared for agriculture, logging, hydroelectric and transportation projects and other changes in land use. However, the off-site environmental impacts of surface mining can be very extensive, due to erosion and runoff resulting in siltation and deterioration of water quality in nearby rivers, lakes and reservoirs. To avoid these adverse environmental impacts, effective forest restoration on mined sites is required. This requires careful planning and the integration of mining and rehabilitation operations based on sound silvicultural and ecological knowledge and principles (Bradshaw, 1987, 1997). Proper site preparation, including mine-site 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 and 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 natural forests (Knowles and Parrotta, 1995).

Forest restoration programs by mining companies in Brazil (Majer, 1992, 1996; Gaunt and Bliss, 1993; Knowles and Parrotta, 1995 ), Australia (Tacey, 1979) and other tropical countries have usually relied on planting of either native or exotic forest species to rapidly establish tree cover on reclaimed mine sites 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. (MRN) has developed a reforestation program aimed at restoring the forest cover destroyed at a rate of approximately 100 ha year$^{-1}$ during bauxite ore extraction at Trombetas in western Pará State (Knowles and Parrotta, 1995). The MRN 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$^{-1}$, has been the standard reforestation technique used at the Trombetas mine since the mid-1980s. This more sophisticated reforestation approach involving mixed native species plantings 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.

At the Trombetas mine site, 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 using mainly short-lived, native early successional trees, and mixed plantings of mostly exotic species. Also present at this site are small areas where: (1) the standard mixed native species treatments were applied but, due to operational failures (inadequate topsoil application), subsequent tree growth was greatly reduced; and (2) site preparation and topsoil replacement protocols were followed, but where trees were not planted. The presence of these developing forest stands of similar age (9–13 years) established using different methods, or treatments, provided a unique opportunity to evaluate their relative value for forest restoration. Studies were therefore undertaken to compare the structure, floristic composition, successional status and sustainability of these treatments with reference to the old-growth forests surrounding the mine site. In this paper, we will summarize the major results of these studies, in the hope that they will be of use in mine restoration programs elsewhere in the tropics. Further details of these studies can be found in Parrotta et al. (1997), Parrotta and Knowles (1999).

## 2. Methods

### 2.1. Study location

The Trombetas bauxite mine 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). Mean annual rainfall at Porto Trombetas (1970–1994) is $2185 \pm 64$ (S.E.) mm, with distinctly dry (winter) and wet (summer) seasons; mean monthly rainfall exceeds 100 mm in all months except July–October. The mean maximum and minimum temperatures are, respectively, 34.6 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 have average canopy heights of 20–35 m, with emergent trees up to 45 m tall (Knowles and Parrotta, 1995, 1997). The forests surrounding the mine were, until recently, largely inaccessible and undisturbed by hunting or forest clearing for the past 200–300 years. Consequently, wildlife diversity in the vicinity of the mine remains high and includes the large terrestrial and arboreal mammals, bats and birds that play critical roles in forest succession.


Fig. 1. Location of the study site.

### 2.2. Native forest species propagation and performance assessment

During the 1980s, 160 species of trees (from 42 families) found in the old-growth forests surrounding the mine site were systematically evaluated to determine the most cost-effective methods for their propagation and to assess their early performance after planting at the mine site. This research program, described in detail in Knowles and Parrotta (1995), involved evaluations of fruiting phenology, seed viability, seed germination treatments, propagation methods (direct seeding, use of stumped saplings, wildlings, and nursery-grown seedlings), and early survival and growth during the first 2 years after outplanting under operational conditions.

### 2.3. Reforestation treatments

The study areas were located on the eastern side of the Saracá plateau on sites mined between 1982 and 1986, and next to undisturbed old-growth forest. For all treatments described in Table 1 (with the exception of the mixed native species ‘failure’), the standard reclamation and site preparation sequence was followed, which includes leveling of the clay overburden, replacement of approximately 15 cm of topsoil and woody debris (removed from the site prior to mining and stockpiled for up to 6 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 $2 \times 2$ m spacing (2500 trees ha$^{-1}$) using seeds, stumped saplings and/or potted seedlings, depending on species and treatment.

### 2.4. Forest stand structure and floristics

Between 1995 and 1997, stand structure, floristic composition, and forest floor development were evaluated for all treatments and in old-growth forests on the Saracá plateau using replicated 10-m diameter circular plots (78.5 m$^2$) as the standard measuring unit. Due to stand area dif-

Table 1
Reforestation treatments studied at the Trombetas bauxite-mined site

| Treatment | Description | Total Area | Year established |
|---|---|---|---|
| Mixed native species (MNS) | Mixed species plantings of ca. 70 native forest tree species of different successional stages | 100 ha | 1985 |
| Mixed native species 'failure' | As MNS, but poor survival (<25%) of planted trees apparently due to inadequate site preparation, specifically insufficient topsoil application | Small areas (<0.1 ha) in MNS treatment | 1985 |
| Mixed commercial species | Mixed species plantings of *Eucalyptus camaldulensis*, *Eucalyptus citriodora*, *Eucalyptus pellita*, *Eucalyptus torreliana*, *Eucalyptus urophylla*, *Acacia mangium* and *Sclerolobium paniculatum*. | 2.0 ha | 1987 |
| Direct seeding | Mixed species plantings of 48 mainly short-lived native forest taxa; mowed at 40 cm height to stimulate sprouting in 1987 | 17 ha | 1986 |
| Natural regeneration | Regeneration initiated from seeds in applied topsoil | Four sites, 0.3–1.0 ha each | 1984–1987 |

ferences among treatments, the total sampling area varied among treatments. Study plots were located randomly within the study sites in the natural regeneration, mixed commercial species, and mixed native species 'failure' treatments. In the remaining two treatments (mixed native species, direct seeding), these plots were established at varying distances from the intact old-growth forest along the edge of the plateau towards the interior of the Saracá plateau, with plot centers 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. Old-growth 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, a complete inventory was made of all adult and juvenile trees and shrubs, vines, herbs, and grasses. For each of these floristic categories, the total numbers of individuals (or clumps, for grasses) of each species were recorded. For trees and shrubs (including palms), height and stem diameters (at 1.3 m = dbh) for trees $\geq 2$ m in height were also measured. Height and stem diameter data 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' long-term observations of the local tree flora, and their regeneration origin, i.e. whether they were planted or naturally regenerated from either the applied soil seed bank or subsequent inputs from surrounding natural forests. 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 ten randomly located points within each plot, with plot means for each horizon used for subsequent analyses.

### *2.5. Data analysis*

Numbers or individuals per square meter and basal area (for trees $\geq 2$ m tall) were calculated for all species in each treatment. Species richness for each floristic category was expressed simply as the number of species present per plot. Based on the total plant species list for all plots in each treatment, Sorensen's quotient of similarity ($I$) was calculated for the tree flora to assess the degree of similarity between restoration treatments and the old-growth forest. Mean canopy closure, canopy height, tree basal area, litter and humus depth, plant density, and species richness for woody species, vines, herbs and grasses were compared among treatments using unpaired two-group $t$-tests.

## 3. Results and discussion

### 3.1. Tree species propagation and performance

The propagation methods tested by MRN for 160 native tree species at the reclaimed mine site were, in order of increasing cost: direct seeding, planting of stumped saplings (i.e. saplings collected from the wild whose tops and all but taproots are removed), wild seedlings, and nursery-grown seedlings. It was found that direct seeding was suitable (with survival rates $\geq 75\%$) for 21% of the species studied; these species generally had large seeds ($> 2$ cm long and broad) that could be conveniently handled by planters in the field. For an additional 13 species (8%), stumped saplings were the most economical and viable option. Of the remaining 113 tree species, wildlings collected from the surrounding old-growth forests was the most cost-effective planting stock option for 78 species (49%), while only 35 species, or 22% of the total, could not be propagated by these more economical means and required raising seedlings from seed in the nursery.

The seeds of many tropical tree species require mechanical or chemical scarification to speed their germination. Pre-sowing treatments can, however, add significantly to the cost of nursery production. On an operational scale such as that practiced by MRN at Trombetas, it is important to determine the least expensive methods for seed handling to minimize these expenses. Of the 160 native Amazonian tree species studied, however, 71% were found to not require either method of scarification to break seed dormancy. Twenty-one percent required mechanical scarification and only 7% required chemical scarification (soaking in concentrated $H_2SO_4$). These findings were used to develop cost-effective strategies for planting stock selection and, for nursery-grown seedlings, seed handling protocols.

Evaluations of post-plantation adaptability and early growth found that 37% of the 160 tree species studied were well adapted to the open site conditions of the reforestation site, showing vigorous shoot growth and survival rates of $\geq 75\%$ during the first 2 years after planting. An additional 30 species (19%) were rated as 'fair', with good shoot growth and survival rates of 50–75%; these species prefer partial shading during the first year after planting, but grow vigorously under full sun thereafter. The remaining 71 species (44%) performed poorly during the first 2 years, with survival rates $< 50\%$ and stagnant shoot growth; species in this group generally require shade, at least during the first 2 years of their development, and are recommended for enrichment plantings beneath the closed canopy of plantations established using the better-adapted species, preferably about 5 years after the initial plantings. Further details on tree species propagation and early performance after planting are provided in Knowles and Parrotta (1995).

### 3.2. Influence of site preparation on forest development

The importance of careful site preparation, particularly topsoil handling, is evident when one compares the structural and floristic development 10 years after planting in sites at the Trombetas mine, where the mixed native species treatment was applied with and without adequate topsoil application during the site preparation phase. As shown in Table 2, tree basal area, canopy height and crown cover percentages were significantly lower in the mixed native species treatment plots with inadequate topsoil application (MNS 'failure') than in plots in which the prescribed site preparation protocols were followed. In the former plots, rates of litter accumulation and humus development were relatively poor. Although the overall density of woody species in these areas was not significantly lower, individuals $> 2$ m tall were relatively uncommon.

There were clear differences in the floristic richness of these sites, the MNS 'failure' plots having significantly fewer (approximately 50%) planted and naturally regenerated tree and shrub species

Table 2
Structural characteristics and tree species diversity in 9–13 year old reforestation plots and old-growth forest at the Trombetas bauxite-mined site[a]

| Treatment | Old-growth ('primary') forest | Mixed native species | MNS 'failure' (insufficient topsoil) | Mixed commercial species | Direct seeding | Natural regeneration |
|---|---|---|---|---|---|---|
| Year established | ? | 1985 | 1985 | 1987 | 1986 | 1983–1987 |
| Years since establishment | >200? | 10 | 10 | 9 | 10 | 9–13 |
| Sample area ($m^2$) | 628 | 2512 | 471 | 628 | 1256 | 942 |
| Number of sample plots/treatment ($n$) | 8 | 32 | 6 | 8 | 16 | 12 |
| Crown cover (%) | $75.7^{A}$ | $56.1^{CD}$ | $27.8^{E}$ | $59.8^{BC}$ | $53.2^{CD}$ | $63.5^{B}$ |
| Canopy height (m)[b] | $21.6^{A}$ | $10.6^{B}$ | $4.5^{C}$ | $17.4^{A}$ | $10.4^{B}$ | $11.7^{B}$ |
| Tree basal area ($m^2\ ha^{-1}$) | $76.5^{A}$ | $13.9^{E}$ | $1.5^{F}$ | $24.9^{B}$ | $16.8^{DE}$ | $19.6^{CD}$ |
| Litter depth (mm) | $29.4^{B}$ | $32.4^{B}$ | $14.0^{C}$ | $42.7^{A}$ | $32.7^{B}$ | $46.0^{A}$ |
| Humus depth (mm) | $13.3^{A}$ | $8.3^{AB}$ | $1.1^{C}$ | $5.7^{B}$ | $6.9^{AB}$ | $6.3^{AB}$ |
| *Density (number of individuals $m^{-2}$)* | | | | | | |
| Woody species (all) | $5.47^{A}$ | $3.06^{BC}$ | $2.85^{BC}$ | $1.32^{D}$ | $3.47^{B}$ | $1.55^{CD}$ |
| Planted | 0 | $0.18^{B}$ | $0.05^{C}$ | $0.15^{B}$ | $0.52^{A}$ | 0 |
| Other[c] | $5.47^{A}$ | $2.88^{BC}$ | $2.80^{BC}$ | $1.17^{D}$ | $3.04^{B}$ | $1.55^{CD}$ |
| Woody species, <2 m tall | $5.04^{A}$ | $2.66^{BC}$ | $2.75^{B}$ | $1.04^{D}$ | $2.93^{B}$ | $1.19^{CD}$ |
| Woody species, >2 m tall | $0.43^{B}$ | $0.40^{B}$ | $0.13^{C}$ | $0.28^{B}$ | $0.54^{A}$ | $0.36^{B}$ |
| Vines | $0.48^{B}$ | $0.40^{B}$ | $0.24^{B}$ | $0.34^{B}$ | $0.82^{A}$ | $0.43^{B}$ |
| Grasses | $0.17^{E}$ | $0.40^{D}$ | $2.74^{A}$ | $1.16^{B}$ | $1.14^{BC}$ | $0.52^{CD}$ |
| Herbs | $0.36^{B}$ | $0.019^{C}$ | 0 | $1.18^{A}$ | $0.18^{B}$ | $0.025^{C}$ |
| *Species richness (no. species/plot)* | | | | | | |
| Woody species (all) | $67.3^{A}$ | $28.5^{C}$ | $15.5^{E}$ | $17.5^{E}$ | $35.4^{B}$ | $23.1^{D}$ |
| Planted | 0 | $8.8^{A}$ | $4.2^{B}$ | $5.5^{B}$ | $11.6^{A}$ | 0 |
| Other[c] | $67.3^{A}$ | $23.7^{B}$ | $11.8^{C}$ | $12.3^{C}$ | $28.6^{B}$ | $23.1^{B}$ |
| Woody species, <2 m tall | $59.8^{A}$ | $21.2^{C}$ | $13.3^{DE}$ | $9.8^{E}$ | $31.6^{B}$ | $16.0^{D}$ |
| Woody species, >2 m tall | $21.5^{A}$ | $14.6^{B}$ | $6.5^{D}$ | $11.4^{C}$ | $11.6^{C}$ | $11.4^{C}$ |
| *Sorensen's Index of Similarity (I)*[d] | | | | | | |
| Woody species (all) | 1.00 | 0.51 | 0.22 | 0.16 | 0.50 | 0.40 |

[a] Similar superscript letters (A, B, C, D, E) within a row indicate that means were not significantly different between treatments ($P<0.05$, $t$-test).
[b] Calculated as the mean of plot averages for the five tallest trees per plot.
[c] 'Other' species include those regenerating from the seed bank in applied soil or arising from seed inputs from surrounding old-growth forests.
[d] Comparisons with surrounding old-growth forest. See Table 4 for list of tree and shrub species surveyed. A complete plant lists from old-growth forest and restoration treatments is available from the authors.

in both the seedling ( < 2 m tall) and larger ( > 2 m tall) size classes. As a result of poor performance of planted trees, the MNS ‘failure’ plots tended to be dominated by persistent fire-prone grasses and a very limited number of short-lived early secondary forest species that can survive under such conditions.

### *3.3. The role of landscape floristics and wildlife in restoration processes*

In all of the plantation treatments studied, the total number of tree and shrub species present in study plots greatly exceeded the number of planted species. Regeneration from seeds in the applied topsoil and that resulting from seed inputs from nearby old-growth forest stands comprised between 70 and 83% of the total tree species richness, and 88–98% of the total numbers of seedlings and larger individuals in the study plots (Tables 2 and 4). Based on the authors’ knowledge of the seed viability, it was estimated that approximately 40% of the tree species regenerating in the study plots could have survived in the soil seed bank during the 6- to 12-month period between topsoil stockpiling and reapplication to the reforestation areas. The remainder of these species, up to 75 in the mixed native species treatment, were considered to be the result of post-plantation seed inputs, facilitated mainly by the birds, bats and terrestrial mammals that are the primary agents of seed dispersal in the upland forests of this region (Knowles and Parrotta, 1997; Parrotta et al. 1997).

Tree species whose seeds are dispersed by wildlife were significantly more abundant in study plots located closer to the undisturbed forests surrounding the mine site than in those further from the old-growth forest edge. Although there was abundant colonization by woody forest species up to 640 m away from the old-growth forest edge in the mixed native species treatment, the density and diversity of colonizing species was inversely correlated with distance into the reforestation area (Fig. 2).

These results suggest that seed dispersal may be limiting the process of tree flora enrichment within the reforestation area. A comparison of seed sizes between tree species regenerating in the reforestation area and those found in the old-growth forest (Fig. 3) indicates that, while the smaller-seeded tree flora are already well represented in the reforestation area, larger-seeded species are less well represented. These include members of the most important tree families (in terms of dominance and ecological function) in the old-growth forest, i.e. Annonaceae, Chrysobalanaceae, Lauraceae, Palmae and Sapotaceae. Tree species from these families also tended to perform very poorly when planted under open conditions at this site (Knowles and Parrotta, 1995).

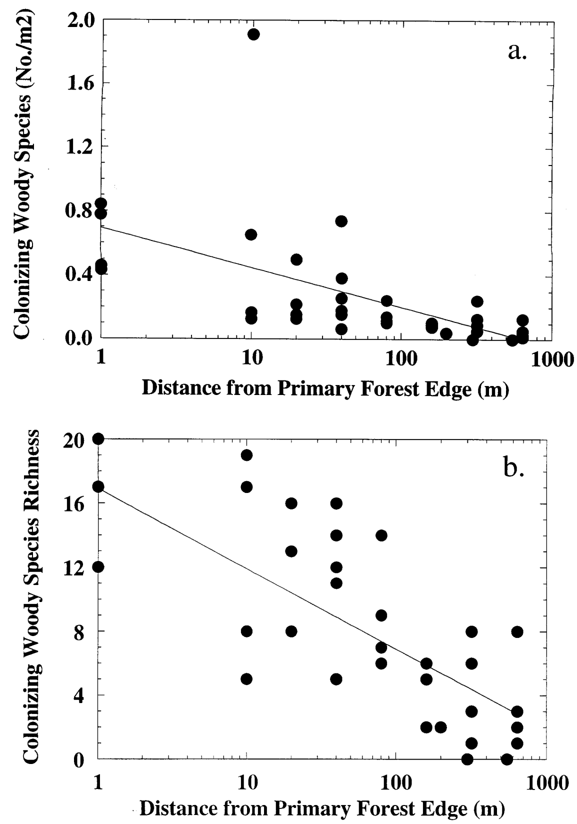



Fig. 2. Relation between understory regeneration of woody old-growth forest colonists and distance from old-growth (‘primary’) forest in 10-year-old mixed native species plots at Trombetas bauxite mined site. (a) Plot distance from old-growth forest, $y = 0.69 - 0.24 \log_{10} x$ ($r^2 = 0.33$, $F = 17.6$; $P < 0.001$). (b) Plot distance from old-growth forest, $y = 18.8 - 4.96 \log_{10} x$ ($r^2 = 0.54$, $F = 41.6$, $P < 0.001$).

Table 4
Tree and shrub species surveyed in old-growth forests and in 9- to 12-year-old restoration treatments at the Trombetas bauxite mine site[a]

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| ANACARDIACEAE | | | | | | | | | |
| *Anacardium giganteum* | Caju acu | X | | | | | | Fauna | 4 |
| *Astronium lecointei* | Muiracatiara | X | P | X | | | X | Wind | 4 |
| *Spondias mombin* | Taperebá | | P | | | P | X | Fauna | 2 |
| *Tapirira guianensis* | Tatapiririca | X | P | X | | X | X | Fauna | 2 |
| Unidentified | Cajarana | X | | | | | | ? | 2 |
| ANNONACEAE | | | | | | | | | |
| *Annona ambotay* | Envira taia | X | X | X | | | | Fauna | 1 |
| *Annona* sp. | Envira ata | X | | | | | | Fauna | 2 |
| *Duguetia riparia* | Envira branca | X | P | X | X | X | X | Fauna | 1 |
| *Duguetia* sp. | Envira jaca | X | | | | | | Fauna | 2 |
| *Guatteria* sp. | Envira pindauba preta | X | X | | | | X | Fauna | 2 |
| *Guatteria* sp. | Envira bananinha | X | | | | | | Fauna | 2 |
| *Guatteria* sp. | Envira preta | X | P | | X | X | X | Fauna | 2 |
| *Rollinia* sp. | Envira conde | | P | X | X | P | X | Fauna | 1 |
| *Bocageopsis* sp. | Envira turí preta | X | X | | | | X | Fauna | 1 |
| *Bocageopsis* sp. | Envira turí vermelho | X | X | | | | | Fauna | 1 |
| *Xylopia* sp. | Envira pindauba amarela | X | | | | | | Fauna | 1 |
| APOCYNACEAE | | | | | | | | | |
| *Aspidospermum exalatum* | Araracanga | X | X | | | P | X | Wind | 4 |
| *Aspidospermum oblongum* | Carapanauba | X | P | | X | P | X | Wind | 3 |
| *Aspidospermum* sp. | Muirajussara | | P | X | | | | Wind | 4 |
| *Couma guianensis* | Sorva | | P | | | | | Fauna | 2 |
| *Geissospermum sericeum* | Acariquara branca | X | X | | | | | Fauna | 3 |
| *Geissospermum* sp. | Fel de veado | | | | | | | Fauna | 1 |
| *Tabernaemontana* sp. | Colhoes de bode | X | | | | | | Fauna | 1 |
| Unidentified | Bucheira | | P | | | | X | Wind | 2 |
| ARALIACEAE | | | | | | | | | |
| *Schlefflera morototoni* | Morototó | | X | | X | X | | Fauna | 2 |
| BIGNONIACEAE | | | | | | | | | |
| *Jacaranda copaia* | Parapará | | P | | X | X | X | Wind | 2 |
| *Tabebuia impetignosa* | Pau d'árco roxo | | X | | | X | X | Wind | 4 |
| *Tabebuia serratifolia* | Pau d'árco amarelo | X | P | X | | P | | Wind | 4 |
| BORAGINACEAE | | | | | | | | | |
| *Cordia alliodora* | Uruazeiro | X | X | | | X | | Fauna | 2 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| BURSERACEAE | | | | | | | | | |
| *Hemicrepidospermum rhoifolium* | Breu branco | X | X | | | X | X | Fauna | 2 |
| *Protium apiculatum* | Breu vermelho | X | X | | | X | | Fauna | 3 |
| *Protium* sp. | Breu amarelo | X | | | | | | Fauna | 2 |
| *Tetragastris panamensis* | Breu preto | X | X | | | X | X | Fauna | 3 |
| *Trattinnickia rhoifolia* | Breu sucuruba | | P | | | X | X | Fauna | 4 |
| CELASTRACEAE | | | | | | | | | |
| *Goupia glabra* | Cupiuba | | P | X | X | P | X | Fauna | 4 |
| CHRYSOBALANACAEAE | | | | | | | | | |
| *Couepia bracteosa* | Pajurá | X | X | X | | X | X | Fauna | 3 |
| *Couepia longipendunculo* | Castanha de galinha | X | P | | | | | Fauna | 3 |
| *Couepia* sp. | Pajurá de anta | X | | | | | | Fauna | 3 |
| *Hirtella* sp. | | X | | | | | | Fauna | 2 |
| *Hirtella* sp. | Jequitaia | X | | | | | | Fauna | 1 |
| *Licania* cf. micrantha | Caraiperana | X | P | | | X | X | Fauna | 3 |
| *Licania* sp. | Macucu | X | | | | | | Fauna | 2 |
| *Licania* sp. | Caripe de vidro | X | | | | | | Fauna | 4 |
| *Licania* sp. | Macucu vermelho | X | | | | | | Fauna | 2 |
| *Licania* sp. | Caripe | X | | | | | | Fauna | 4 |
| CLUSIACEAE | | | | | | | | | |
| *Clusia* sp. | Clusia | X | X | X | X | X | X | Fauna | 2 |
| COMBRETACEAE | | | | | | | | | |
| *Buchenavia* sp. | Cuiarana | X | P | X | | P | | Fauna | 4 |
| Unidentified | Cuiaranazinha | | | | | X | | Fauna | 4 |
| CONNARACEAE | | | | | | | | | |
| *Connarus* sp. | Arara-mira | X | | | | | | Fauna | 2 |
| *Connarus* sp. | | X | | | | | | Fauna | 1 |
| EBENACEAE | | | | | | | | | |
| *Diospyros* sp. | Caqui | X | X | | | X | X | Fauna | 4 |
| ELAEOCARPACEAE | | | | | | | | Fauna | |
| *Sloanea* spp. | Urucurana | X | | | | X | | Fauna | 3 |
| EUPHORBIACEAE | | | | | | | | | |
| Unidentified | Caxixá | | P | | | | X | Fauna | 1 |
| *Conceveiba* spp. | Pau de índio | X | P | X | | X | X | Fauna | 1 |
| *Croton* sp. | Pau gaviota | X | P | X | | X | X | Fauna | 1 |
| *Hevea guianensis* | Seringa itauba | X | P | X | | X | | Fauna | 3 |
| *Joannesia princips* | Boleira | | P | X | | X | | Fauna | 2 |
| *Mabea* sp. | Taquari | X | | | | | | Fauna | 1 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| FLACOURTIACEAE | | | | | | | | | |
| *Casearia* sp. | Caferana | X | | | | X | | Fauna | 1 |
| *Casearia* sp. | | | X | | | | | Fauna | 1 |
| *Casearia* sp. | Canela de velha | X | | | | X | | Fauna | 1 |
| *Laetia procera* | Pau jacaré | | P | X | X | X | X | Fauna | 3 |
| GUTTIFERAE | | | | | | | | | |
| *Platonia* sp. | Bacuri mirim | X | | | | | | Fauna | 2 |
| *Vismia guianensis* | Lacre marrom | | P | X | X | X | X | Fauna | 1 |
| *Vismia cayennensis* | Lacre branco | X | X | X | | X | X | Fauna | 1 |
| *Vismia* sp. | Lacre vermelho | | P | X | X | X | X | Fauna | 1 |
| HUMIRIACEAE | | | | | | | | | |
| *Duckesia sericea* | Uchi corôa | X | X | | X | | X | Fauna | 3 |
| *Endopleura uchi* | Uchi pucu | X | X | X | X | P | X | Fauna | 3 |
| *Sacoglottis mattogrossensis* | Achuá | X | P | X | | X | X | Fauna | 3 |
| *Vantanea paraensis* | Uchi morcego | X | X | X | X | | X | Fauna | 3 |
| LAURACEAE | | | | | | | | | |
| *Aniba hostmaniana* | Louro amarelo | X | | | | | X | Fauna | 3 |
| *Aniba parviflora* | Louro pucherin | X | X | | | | | Fauna | 2 |
| *Aniba* cf. *Permollis* | Louro rosa | X | | | | X | | Fauna | 2 |
| *Aniba* sp. | Louro fofo | X | | | | | | Fauna | 2 |
| *Aniba* sp. | Louro precioso | X | | | | | | Fauna | 3 |
| *Mezilaurus itauba* | Itauba amarela | | X | | | | X | Fauna | 3 |
| *Nectandra rosa* | Louro vermelho | X | | | | | | Fauna | 4 |
| *Ocotea fragrantissima* | Louro canela | | X | | | | | Fauna | 3 |
| *Ocotea guianensis* | Louro prata | X | X | | | X | | Fauna | 2 |
| *Ocotea myriantha* | Louro abacate | X | X | | X | X | X | Fauna | 3 |
| *Ocotea* sp. | Louro branco | X | X | | | X | X | Fauna | 2 |
| *Ocotea* sp. | Louro pequeno | X | | | | X | | Fauna | 3 |
| *Ocotea* sp. | Louro preto | X | | | | | | Fauna | 3 |
| Unidentified | Louro chumbo | X | | | | | | Fauna | 3 |
| LECYTHIDACEAE | | | | | | | | Fauna | |
| *Bertholletia excelsa* | Castanha do Pará | | P | X | | P | | Fauna | 4 |
| *Cariniana micrantha* | Taurí côco | | | | | P | | Wind | 4 |
| *Eschweilera* sp. | Matamatá preta | X | | | | | | Fauna | 3 |
| *Eschweilera* sp. | Matamatá | X | X | | | X | | Fauna | 3 |
| *Holopyxidium* sp. | Jarana | X | | | | | | Fauna | 3 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| LEGUMINOSAE-CAESALPINIOIDEAE | | | | | | | | | |
| *Cassia spruceana* | Faveira marimarí grande t.f. | | X | | | P | | Fauna | 2 |
| *Cassia* sp. | Cassia piolho | | P | X | | P | | Fauna | 1 |
| *Cassia* sp. | Faveira marimarí peq. t.f. | | P | | | P | X | Fauna | 1 |
| *Dialium guianensis* | Jutaí pororoca | X | | | | | | Fauna | 4 |
| *Hymenaea courbaril* | Jutaí | X | P | X | | | X | Fauna | 4 |
| *Peltogyne paniculata* | Mulateiro | | | | | | X | Wind | 3 |
| *Peltogyne paradoxa* | Coataquicaua | X | X | X | | | X | Wind | 3 |
| *Sclerolobium melanocarpum* | Tachí vermelho | X | X | | | | | Wind | 2 |
| *Sclerolobium paniculatum* | Tachí dos campos | | P | X | P | P | X | Wind | 1 |
| *Tachigali myrmecophylla* | Tachí pitomba | X | X | | | | | Wind | 2 |
| *Tachigali* sp. | Tachi preto folha miuda | X | | | | | | Wind | 3 |
| LEGUMINOSAE-MIMOSOIDEAE | | | | | | | | | |
| *Acacia auriculiformis* | Acacia auriculiformis | | X | | | P | | Fauna | 1 |
| *Acacia mangium* | Acacia mangium | | X | X | P | P | X | Fauna | 1 |
| *Adenanthera pavonia* | Carolina | | | | | P | | ? | 2 |
| *Cedralinga catanaeformis* | Cedrorana | | P | | | | | Wind | 4 |
| *Dinizia excelsa* | Angelim pedra | | P | | | P | X | Wind | 4 |
| *Enterolobium maximum* | Faveira timboril | X | P | | | P | | Fauna | 4 |
| *Enterolobium schomburgkii* | Faveira de rosca | | X | | | P | | Fauna | 3 |
| *Inga alba* | Ingá branca | X | X | | | X | X | Fauna | 1 |
| *Inga falcisti* | Ingá xixica | X | X | | | X | X | Fauna | 2 |
| *Inga obtusata* | Ingá veluda | X | X | | | X | X | Fauna | 1 |
| *Inga* sp. | Ingá cipo | | X | | X | X | X | Fauna | 1 |
| *Inga* sp. | Ingá escamosa | | | | | X | | Fauna | 1 |
| *Inga* sp. | Ingá guariba | X | X | | | | | Fauna | 1 |
| *Inga* sp. | Ingá dura | | | | | | X | Fauna | 1 |
| *Inga* sp. | Ingá grande | X | | | | | | Fauna | 2 |
| *Inga* sp. | Ingá vermelha | X | | | | | | Fauna | 2 |
| *Leucaena leucocephala* | Leucaena | | | | | P | | Wind | 1 |
| *Paraserianthes falcataria* | Albizia falcata | | | | | P | X | Wind | 1 |
| *Parkia gigantocarpa* | Faveira arara tucupí | | P | X | | P | X | Fauna | 3 |
| *Parkia oppositifolia* | Faveira japacamim | | X | X | | X | | Fauna | 3 |
| *Parkia pendula* | Faveira bolota | | X | | | P | | Fauna | 3 |
| *Parkia ulei* | Faveira arara II | | P | X | X | | X | Fauna | 3 |
| *Parkia* sp. | Faveira rabo de arara | | | | | P | | Fauna | 3 |
| *Piptadenia suaveolens* | Faveira timborana | X | P | | | X | X | Wind | 3 |
| *Pithecellobium racemosum* | Angelim rajado | X | | | | X | | Fauna | 4 |
| *Pithecellobium* sp. | Faveira dentinha | | P | | | X | | Fauna | 2 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| *Stryphnodendron pulcherrimum* | Faveira camuzé | | P | | X | P | X | Fauna | 2 |
| *Stryphnodendron* sp. | Faveira pituí | X | | | | X | | Fauna | 3 |
| Unidentified | Faveira mapuchiqui | X | X | | | | | ? | 3 |
| Unidentified | Faveira mucuna | | X | | | X | | ? | 2 |
| LEGUMINOSAE-PAPILIONOIDEAE | | | | | | | | | |
| *Andira retusa* | Andira-uchi | | X | | | | | Fauna | 4 |
| *Bowdichia* cf. *Nitida* | Sucupira amarela | | X | X | | | | Wind | 3 |
| *Bowdichia* sp. | Sucupira preta | X | P | | | P | | Wind | 3 |
| *Clitoria racemosa* | Palheteira | | P | X | | | | Fauna | 1 |
| *Dalbergia spruceana* | Jacarandá do Pará | | P | | | | | Wind | 2 |
| *Dipteryx magnifica* | Cumarú rosa | | P | | | | | Fauna | 4 |
| *Dipteryx odorata* | Cumarú | | P | | | P | X | Fauna | 4 |
| *Hymenolobium excelsum* | Angelim da mata | X | X | | | P | | Wind | 4 |
| *Hymenolobium* sp. | Angelim aroeira | | P | X | | X | X | Wind | 4 |
| *Ormosia discolor* | Tento | | X | | | | | Fauna | 3 |
| *Ormosia* sp. | Tento monocor vermelho | | | | | P | | Fauna | 3 |
| *Platymiscium duckei* | Macacaúba da terra firme | | P | | | | | Wind | 3 |
| *Pterocarpus rohrii* | Mututí da terra firme | | | | | | | Wind | 2 |
| *Swartzia corrugata* | Coração de negro | X | X | | | | | Fauna | 2 |
| *Swartzia polyphylla* | Pitaíca | | P | | | | | Fauna | 3 |
| *Swartzia* spp. | Gombeira | X | | | | X | | Fauna | 3 |
| *Vatairea sericea* | Faveira amargosa | | P | X | | | X | Wind | 3 |
| MALPIGHIACEAE | | | | | | | | | |
| *Byrsonima* sp. | Muricí da mata | X | P | X | X | P | X | Fauna | 2 |
| *Byrsonima* sp. | Mirixí | | P | X | | | | Fauna | 1 |
| MELASTOMATACEAE | | | | | | | | | |
| *Belucia dichotoma* | Muúba | | P | X | X | X | X | Fauna | 1 |
| *Miconia longifolia* | Sapateiro | | P | X | X | X | | Fauna | 1 |
| *Miconia* sp. | Maramara branca | X | X | | X | X | X | Fauna | 1 |
| *Miconia* sp. | Maramara preta | X | X | | X | X | X | Fauna | 1 |
| *Miconia* sp. | Miconia arbusto | | X | X | X | X | X | Fauna | 1 |
| *Mouriri plasscharti* | Muiraúba | X | X | | | X | | Fauna | 3 |
| MELIACEAE | | | | | | | | | |
| *Carapa guianensis* | Andiroba | | P | | | | | Fauna | 3 |
| *Guarea* sp. | Jatoa branca | X | | | | | | Fauna | 2 |
| *Guarea* sp. | Jatoa vermelha | X | | | | | | Fauna | 2 |
| *Trichilia lecointei* | Jataúba | X | | | | X | | Fauna | 4 |
| MONIMIACEAE | | | | | | | | | |
| *Siparuna amazonica* | Capitiu | X | X | | | | X | Fauna | 1 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| MORACEAE | | | | | | | | | |
| *Brosimum lactescens* | Janitá | X | X | | | X | X | Fauna | 1 |
| *Brosimum potabile* | Amapa doce | X | X | | X | X | | Fauna | 4 |
| *Brosimum rubescens* | Muirapiranga | X | X | | | P | | Fauna | 4 |
| *Cecropia* sp. | Imbauba | X | X | X | X | X | X | Fauna | 1 |
| *Clarisia racemosa* | Guariuba | X | | | | X | | Fauna | 1 |
| *Ficus* sp. | Apui | | X | | | X | X | Fauna | 2 |
| *Noyera mollis* | Muiratinga preta | X | X | | | X | X | Fauna | 3 |
| *Olmedia perebaea* | Muiratinga amarela | X | | | | | | Fauna | 3 |
| *Piratinera guianensis* | Miurapinima | X | | | | | | Fauna | 3 |
| *Pourouma* sp. | Imbaubarana | X | X | | | X | | Fauna | 1 |
| MYRISTICACEAE | | | | | | | | Fauna | |
| *Iryanthera sagotiana* | Uccubarana | X | | | | | | Fauna | 2 |
| *Virola multicostata* | Ucuuba preta | X | X | | | X | | Fauna | 3 |
| *Virola* sp. | Ucuuba vermelha | X | X | | | X | | Fauna | 3 |
| MYRTACEAE | | | | | | | | | |
| *Eucalyptus camaldulensis* | Eucalyptus camaldulensis | | | | P | | | Wind | 2 |
| *Eucalyptus citriodora* | Eucalyptus citriodora | | | | P | | | Wind | 2 |
| *Eucalyptus pellita* | Eucalyptus pellita | | | | P | | | Wind | 2 |
| *Eucalyptus torreliana* | Eucalyptus torreliana | | | | P | | | Wind | 2 |
| *Eucalyptus urophylla* | Eucalyptus urophylla | | | | P | | | Wind | 2 |
| *Myrcia* spp. | Pixuna | X | | | | X | | Fauna | 1 |
| *Myrcia fallax* | Murta | X | X | | | X | X | Fauna | 2 |
| *Psidium guajava* | Goiaba | | | | | P | | Fauna | 1 |
| *Psidium guianensis* | Araça | X | X | | | | | Fauna | 1 |
| *Psidium* sp. | Araça pêra | | | | | P | | Fauna | 1 |
| NYCTAGINACEAE | | | | | | | | | |
| *Neea* sp. | Joao mole | X | | | | | | Fauna | 2 |
| OLACACEAE | | | | | | | | | |
| *Minquartia guianensis* | Acariquara | X | X | | | | | Fauna | 2 |
| PALMAE | | | | | | | | | |
| *Astrocaryum munbaca* | Palmeira mumbaca | X | | | | | X | Fauna | 2 |
| *Astrocaryum murumuru* | Palmeira murumuru | X | X | | | X | X | Fauna | 2 |
| *Desmoncus polycanthos* | Palmeira jacitara | | X | | | | | Fauna | 1 |
| *Euterpe oleracea* | Palmeira açai | | X | | | | | Fauna | 1 |
| *Iriatella setigera* | Palmeira paxiuba | X | | | | X | | Fauna | 1 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| *Jessenia bataua* | Palmeira patauá | X | | | | X | | Fauna | 1 |
| *Oenocarpus bacaba* | Palmeira bacaba | X | X | | X | P | X | Fauna | 2 |
| *Oenocarpus minor* | Palmeira bacaba-í | X | | | | | X | Fauna | 2 |
| Unidentified | Palmeira pinaupira | X | | | X | | X | Fauna | 2 |
| Unidentified | Palmeira maraja | X | | | | | | Fauna | 2 |
| Unidentified | Palmeira tucuma | X | | | | | | Fauna | 2 |
| Unidentified | Palmeira ubim | X | | | | | | Fauna | 2 |
| PROTEACEAE | | | | | | | | | |
| *Roupala* sp. | Faieira | X | | | | | | Wind | 4 |
| RUBIACEAE | | | | | | | | | |
| *Duroia* sp. | Purui | X | X | | X | X | X | Fauna | 2 |
| *Duroia* sp. | Pau de remo | X | | | | | | Fauna | 3 |
| *Genipa americana* | Genipapo | | P | | | | | Fauna | 1 |
| *Palicourea* sp. | Erva de rato amarelo | X | X | X | X | X | X | Fauna | 1 |
| *Palicourea* sp. | Erva de rato vermelho | | P | | | P | X | Fauna | 1 |
| Unidentified | | X | X | | | | | Fauna | 2 |
| RUTACEAE | | | | | | | | | |
| *Spathelia excelsa* | Pau para tudo #1 | | | | | | X | Wind | 1 |
| *Zanthoxylum* sp. | Tamanqueira | | | | | | X | ? | 2 |
| SAPINDACEAE | | | | | | | | | |
| *Talisia cupularis* | Pitomba da mata | X | | | | | X | Fauna | 1 |
| Unidentified | | X | | | | | | Fauna | 2 |
| SAPOTACEAE | | | | | | | | | |
| *Chrysophyllum prieurii* | Abiurana vermelha | X | | | | | | Fauna | 3 |
| *Chrysophyllum* sp. | Abiurana casca grossa | X | | | | | | Fauna | 3 |
| *Lucuma dissepala* | Abiurana barriguca | X | | | | | | Fauna | 3 |
| *Manilkara amazonica* | Maparajuba | | | | | X | | Fauna | 4 |
| *Micropholis guianensis* | Abiurana rosadinha | X | X | | | X | | Fauna | 3 |
| *Pouteria krukovii* | Abiurana arrepiadu | X | | | | | | Fauna | 3 |
| *Pouteria trilocularis* | Abiurana amarela | X | | | | | | Fauna | 3 |
| *Pouteria* spp. | Abiurana | X | X | X | | X | | Fauna | 3 |
| *Radlkofarella macrocarpa* | Abiurana cutite | X | | | | | | Fauna | 3 |
| Unidentified | Abiurana moraicica | X | | | | | | Fauna | 3 |
| Unidentified | Abiurana folha grande | X | | | | | | Fauna | 3 |
| Unidentified | Abiurana folha comprida | X | | | | | | Fauna | 2 |
| Unidentified | Abiurana ajara | X | | | | | | Fauna | 3 |
| Unidentified | Abiurana casca fina | X | | | | | | Fauna | 3 |
| Unidentified | Abiurana X | X | | | | | | Fauna | 3 |

Table 4 (*Continued*)

| Scientific name | Common name | Treatment | | | | | | Seed dispersal vector | Tree longevity class |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | | |
| SIMARUBIACEAE | | | | | | | | | |
| *Simarouba amara* | Marupá | X | X | | | X | X | Fauna | 3 |
| STERCULIACEAE | | | | | | | | | |
| *Theobroma sylvestris* | Cacaurana | X | X | | | X | | Fauna | 1 |
| TILIACEAE | | | | | | | | | |
| *Apeiba echinata* | Pente de macaco | | P | X | X | | X | Fauna | 2 |
| *Lueheopsis divicata* | Açoita cavalo | | X | | | | | Wind | 3 |
| ULMACEAE | | | | | | | | | |
| *Trema micrantha* | Curumin | | | | X | | X | Fauna | 1 |
| VERBENACEAE | | | | | | | | | |
| *Lantana camara* | Lantana | | | | | X | X | Fauna | 1 |
| VIOLACEAE | | | | | | | | | |
| *Rinorea guianense* | Acariquarana | X | | | | | | Fauna | 2 |
| *Rinorea* sp. | Jacamin branco | X | X | | | X | X | Fauna | 1 |
| *Rinorea* sp. | Jacamin preto | X | X | X | | X | | Fauna | 1 |
| VOCHYSIACEAE | | | | | | | | | |
| *Erisma uncinatum* | Quarubarana | | | | | | | Wind | 4 |
| *Vochysia obscura* | Quaruba rosa | X | | | | X | | Wind | 2 |
| Unidentified families | | | | | | | | | |
| Unidentified | Acariquarana | X | X | | | | | ? | 2 |
| Unidentified | Canela brava | X | X | | | | | ? | 1 |
| Unidentified | Pau de rego | | X | X | | | | ? | 1 |
| Unidentified | Muiranta | X | | | | | | ? | 2 |
| Unidentified | Papo de mutum | X | | | | | | ? | 1 |
| Unidentified | Olho de veado | X | | | | | | ? | |
| Unidentified | Jameca | X | | | | | | ? | 2 |
| Unidentified | Pau tucandeira | X | X | | | | X | ? | 1 |
| Unidentified | Tapioca | | P | | | X | X | ? | 1 |
| Unidentified | Unknown species | X | X | X | X | X | X | ? | 1 |

[a] Treatment: P, Planted species; X, natural regeneration from soil seed bank or external sources. 1, Native old-growth forest; 2, mixed native species (MNS) plantation; 3, MNS 'failure'; 4, mixed commercial species plantation; 5, direct seeding plantation; 6, natural regeneration. Tree longevity class, average expected life span: 1, <20 years; 2, 20–40 years; 3, 40–80 years; 4, >80 years.

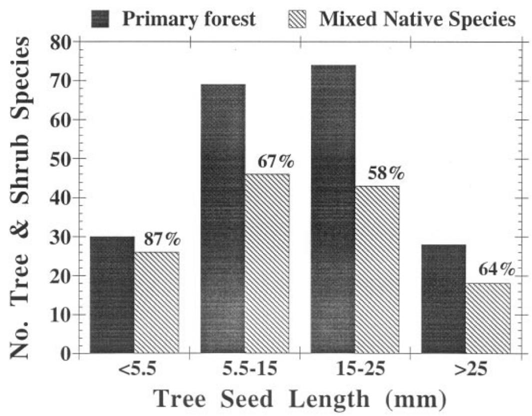



Fig. 3. Distribution of average seed lengths for tree species found in 10-year-old mixed native species plantations and nearby old-growth ('primary') forests at the Trombetas bauxite mine site. Figures above bars indicate the percentages of species in each size class in the plantations relative to the old-growth forest.

In the forests of the Trombetas region, as in other moist tropical forests, larger-seeded species generally depend on a variety of bird and mammal species for their dispersal. Previous surveys of wildlife in the reforestation areas at this site (Pedreira Gonzaga, 1991; Parrotta et al., 1997; Wunderle, 1997) suggest that the regeneration of large-seeded tree species is limited by the relative scarcity in these developing forest stands of these important seed dispersers, i.e., birds such as curassows, toucans, toucanets, and aracaris, terrestrial mammals such as deer, agouti, tapir and opossum, and primates. Assuming that the restoration treatment stands continue to develop both structurally and floristically, larger-seeded species from presently under-represented families may eventually become established as conditions become more favorable for a greater diversity of seed-dispersing birds and mammals, as well as for seed germination and seedling growth. Nonetheless, it is recommended that restoration managers at this site 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.

### *3.4. Effect of overstory composition on forest structure and floristic diversity*

#### *3.4.1. Forest cover and tree density*

Forest canopy cover, tree basal area, litter and humus depths were broadly similar among the mixed native species, mixed commercial species, direct seeding and natural regeneration treatments, although distinctly dissimilar to those of the old-growth forest (Table 2). Average crown cover ranged from 53 to 64% and tree basal area from 13.9 to 24.9 $m^2$ $ha^{-1}$ among restoration treatments, as compared with 76% and 77 $m^2$ $ha^{-1}$ in the old-growth forest. These values were highest in the mixed commercial species and lowest in the mixed native species treatment. Mean canopy heights were significantly greater in the old-growth forest ($21.6 \pm 1.5$ m) and mixed commercial species treatment ($17.4 \pm 0.9$ m) than in the other three treatments (range of means, 10.4–11.7 m). Litter accumulation was significantly greater in the mixed commercial species and natural regeneration treatments (range of mean litter depths, 43–46 mm) than in the direct seeding, mixed native species and old-growth forest stands (range of means, 29–33 mm). Average humus depths ranged from 5.7 mm in the mixed commercial species stands to 13.3 mm in the old-growth forest; treatment differences were significant only between these extremes.

The density of both planted and naturally regenerated woody species was lower in all restoration treatments than in the old-growth forest (Table 2). Planted trees comprised 5.6–15% of the total among the plantation treatments, the remainder arising either from soil seedbank regeneration, subsequent seed inputs from surrounding old-growth forest areas and, for a small number of species, regeneration from planted trees. Seedlings (individuals $<2$ m tall) comprised 77–87% of the total woody species density among restoration treatments and 92% in the old-growth forest. The average density of larger stems ($\geq 2$ m tall) ranged from 0.28 to 0.54 individuals per square meter among restoration treatments and was significantly higher in the direct seeding treatment than in the other restoration treatments or the old-growth forest.

### 3.4.2. Tree species richness

Tree species richness varied greatly among treatments. The total numbers of woody species recorded were 157 in the old-growth forest (representing 39 families), 141 species from 38 families in the mixed native species treatment, 47 species (from 22 families) in the mixed native species 'failure' plots, 40 species (from 21 families) in the mixed commercial species treatment, 117 in the direct seeding treatment (from 37 families), and 86 species (from 32 families) in the natural regeneration treatment (Fig. 4). These totals include planted species, i.e. 7, 42 and 73 in the mixed commercial species, direct seeding, and mixed native species treatments, respectively. If planted species were discounted, the species–area relationships presented in Fig. 4 would appear similar for all but the mixed commercial species stands and the mixed native species 'failure', which contain a smaller number of tree and shrub species than the other treatments.

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

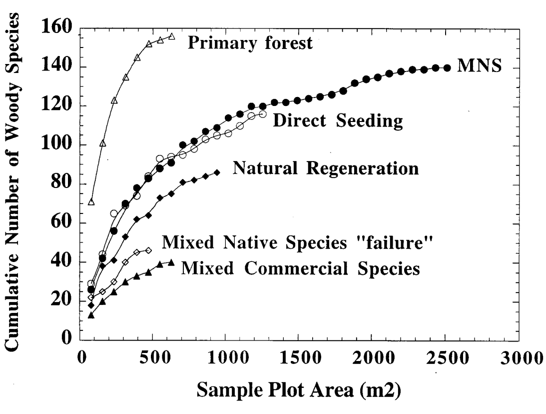



Fig. 4. Species–area relationships for tree, shrub and palm species in restoration treatments and old-growth ('primary') forest. Treatment descriptions are provided in the text; 'MNS' refers to the mixed native species treatment, the standard reforestation practice at the Trombetas mine site.

The mixed native species, direct seeding and natural regeneration treatments contained 55–90% of the total number of species and 82–97% of the total number of families found in the old-growth forest plots. The restoration treatments exhibited a low to moderate degree of floristic similarity to the original old-growth forest, as measured by Sorensen's quotient of similarity ($I$), which 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) (Table 2). Although most of the families present in the old-growth forest tree flora were represented in the natural regeneration, direct seeding and mixed native species treatments, certain important families, including Annonaceae, Chrysobalanaceae, Lauraceae, Palmae and Sapotaceae were, in general, very poorly represented in all restoration treatments, as already discussed.

These general trends are supported by analyses of plot-based (equal area) measurements of species richness (Table 2). The average numbers of tree and shrub species per plot were significantly different among treatments, and increased two-fold from the mixed native species 'failure' and mixed commercial species to the direct seeding treatments, with intermediate values in the natural regeneration and mixed native species treatments. In the old-growth forest, mean tree and shrub species richness was 67.3 species/plot, more than twice that of the direct seeding treatment. Planted species comprised up to one-third of the total in the mixed commercial species, direct seeding and mixed native species 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 species/plot in the mixed commercial species treatment to 31.6 species/plot in the direct seeding treatment. The old-growth forest plots had a significantly larger number of species in this size class (mean, $59.8 \pm 2.6$ species/plot) than all restoration treatments. Woody species richness for larger individuals ($\geq 2$ m tall) was very similar among restoration treatments (range of means, 11.4–14.6 species/plot) but was significantly lower

Table 3
Stand basal area distributions in 9- to 13-year-old restoration treatments and old-growth forest at the Trombetas bauxite mine site[a]

| Treatment | Dominant tree species | Family | %BA | Longevity (years) |
|---|---|---|---|---|
| Natural regeneration | *Cecropia* sp. | Moraceae | 29.6 | <20 |
| | *Byrsonima* sp. | Malpighiaceae | 12.6 | 20–40 |
| | *Vismia guianensis* | Guttiferae | 7.7 | <20 |
| | 33 other species | | 50.1 | |
| Mixed commercial species | *Eucalyptus pellita* | Myrtaceae | 22.6 | 20–40 |
| | *Sclerolobium paniculatum* | Leguminosae (C) | 21.4 | <20 |
| | *Acacia mangium* | Leguminosae (M) | 20.2 | <20 |
| | 16 other species | | 35.8 | |
| Direct seeding | *Sclerolobium paniculatum* | Leguminosae (C) | 53.9 | <20 |
| | 41 other species | | 46.1 | |
| 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 |
| | *Bysonima* sp. | Malpighiaceae | 8.4 | 20–40 |
| | 66 other species | | 50.6 | |
| Mixed native species (insufficient topsoil) | *Vismia* spp. (3) | Guttiferae | 32.1 | <20 |
| | *Joannesia princips* | Euphorbiaceae | 19.2 | 20–40 |
| | 18 other species | | 48.7 | |
| Old-growth 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 |
| | 151 other species | | 48.9 | |

[a] Dominant species comprising approximately 50% of total basal area listed individually.

than in the old-growth forest (mean, $21.5 \pm 1.9$ species/plot).

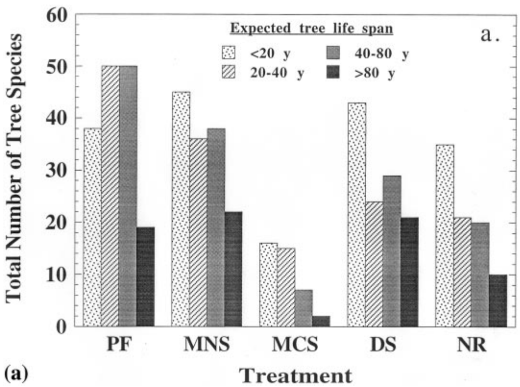
### 3.4.3. Tree species dominance

There were marked differences among treatments in tree species dominance, as measured by basal area percentages (Table 3). In the natural regeneration treatment, the pioneer species *Cecropia* sp., *Byrsonima* sp., and *Vismia guianensis* together comprised 50% of the total basal area. In the mixed commercial species treatment, the planted species *Eucalyptus pellita*, *Sclerolobium paniculatum*, and *Acacia mangium* comprised 64% of the total basal area. In the direct seeding treatment, the dominant species was *S. paniculatum*, with 54% of the total basal area. In the mixed native species treatment, five species: *Croton* sp., *Joanesia princips*, *Bellucia dichotoma*, *Parkia gigantocarpa*, and *Byrsonima* sp. comprised 49% of the total basal area. In the mixed native species 'failure', three species of *Vismia* and *J. princips* comprised 51% of the total basal area. The old-growth 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 old-growth forest in that they exhibited much less marked patterns of dominance by fewer tree species than the other restoration treatments.

### 3.4.4. Tree species life spans

Categorizing tree species by their expected average life spans, differences among treatments are apparent (Fig. 5). For all treatments, the proportions of species and total basal area decrease from younger to older tree life span classes, in contrast to the old-growth forest, where very short-lived ( < 20 years) species are both less numerous and dominant than longer-lived (20–40 or 40–80 years) species. The percentage of species with expected life spans > 40 years is 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 old-growth 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 > 40 years comprise 0.5% of total basal area. The direct seeding treatment is also dominated by short-lived trees, with 88% of the total basal area comprised of species with life spans < 20 years, and relatively poor representation by trees with life spans > 40 years, which comprise 2.6% of the total basal area. The natural regeneration treatment was also dominated by short-lived species, although 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 is found in the mixed native species treatment. In these stands, very short-lived ( < 20 years) tree species comprise 45% of the total basal area, and long-lived species ( > 40 years) 23% of total basal area. In the old-growth forest, very short-lived trees comprised only 6.1% of the total basal area, the remaining basal area distributed among species with expected life spans of 20–40 years (37%), 40–80 years (33%) and > 80 years (24%).



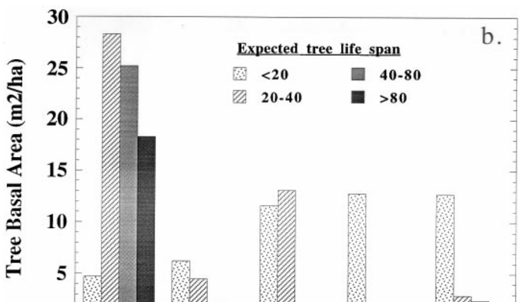




Fig. 5. Expected longevity of planted and naturally regenerating tree species in old-growth forest and 9- to 13-year-old reforestation area study plots at the Trombetas bauxite mine site. (a) Total numbers of tree species; (b) stem basal area ($m^2$ $ha^{-1}$) for trees $\geq 2$ m in height. PF, Old-growth ('primary') forest; MNS, mixed native species treatment; MCS, mixed commercial species treatment; DS, direct seeding treatment; NR, natural regeneration treatment (topsoil application only).

The lesser degree of dominance by shorter-lived tree species, particularly those with expected life spans of less than 20 years, in the mixed native species treatment relative to other plantation treatments suggests that these stands are at a lower risk of arrested succession in the near future. Elsewhere at the Trombetas mine site and in other mine rehabilitation areas in the tropics, the authors have observed the senescence and premature mortality of planted early successional native tree species and short-lived exotic timber species such as eucalyptus and *A. mangium*. Under these conditions, in the absence of vigorous undergrowth comprised of longer-lived native forest trees, such stands are very often subject to rapid invasion by persistent, fire-prone grasses that are known to severely slow, or even preclude, natural forest succession (Uhl and Jordan, 1984; Uhl et al., 1988; Nepstad et al., 1991; Parrotta, 1993; Aide et al., 1995). This risk appears to be minimized in the mixed native species plantation areas that predominate at the Trombetas mine site. In spite of their relatively low productivity at this age compared with that of the other treatments studied, the mixed native species plantation approach adopted by MRN and other mining companies in the region offers the best hope for long-term forest restoration success.

## 4. Conclusions

1. With a modest but timely investment in research, mining companies can develop an efficient, cost-effective system for selecting and propagating a wide array of native tropical forest trees about which basic silvicultural knowledge is lacking, and thereby successfully establish highly diversified mixed native species plantations on an operational scale.
2. Careful site preparation practices, particularly judicious topsoil handling and reapplication prior to tree planting, are essential for the establishment of forest cover, elimination of competing grasses, and acceleration of natural forest succession on reclaimed bauxite mine sites in Amazonia.
3. In addition to the mixed native species plantation approach (the standard reforestation technique at the Trombetas mine site), alternative plantation treatments and reliance on natural regeneration from applied topsoil were found to be effective in re-establishing forest cover and facilitating regeneration of a large number of native forest species during the first 9–13 years. Among treatments, stand basal areas at this age ranged from 18 to 33% of that in the surrounding old-growth forest.
4. Although the less expensive alternatives (commercial species plantings, direct seeding, and reliance solely on natural regeneration from applied topsoil) were more productive (greater basal area development) than the mixed native species treatment, they were generally less well developed in terms of floristic biodiversity. Due to their relatively high degree of dominance by short-lived exotic or native tree species, and somewhat less well-developed understory tree flora, the risk of early canopy mortality and subsequent re-invasion by highly competitive, fire-prone grasses is potentially much greater in these stands than in the mixed native species treatment.
5. Floristic enrichment of the reforestation areas through natural regeneration of 'colonizing' tree species (i.e. those not planted or present in the applied soil seed bank) is largely dependent on seed-dispersing wildlife, mainly bats, birds and terrestrial mammals. The conservation status of the surrounding old-growth forest and an effective ban on hunting greatly facilitated this process. Restoration managers need to be cognizant of the critical role of wildlife in forest re-development, actively encourage wildlife conservation in the surrounding landscape, and design restoration treatments that will provide suitable habitats for a variety of target wildlife species.
6. In the 10-year-old mixed native species plantations, the density and diversity of colonizing primary forest trees was significantly (and positively) affected by the proximity to seed sources in the surrounding old-growth forest. Many large-seeded tree species and others that are considered important components of the region's old-growth forests performed poorly when planted under open conditions and were apparently not colonizing the site due to natural seed dispersal limitations and/or seed and seedling mortality when they did arrive. For these species, restoration managers are advised to carry out enrichment plantings in the understory of established plantations to ensure their successful re-introduction.
7. The results of our studies at the MRN bauxite mine site at Trombetas strongly suggest that the current reforestation practices will eventually be successful in meeting the long-term goal of restoring the complex Amazonian 'terra firme' forest ecosystem destroyed by mining. These findings defy the assumptions of some restorationists that high-diversity forest systems cannot be successfully established through high-diversity planting schemes (Dobson et al., 1997).

## Acknowledgements

This work was conducted in cooperation with the University of Puerto Rico and supported in part by a grant from the World Bank to the International Institute of Tropical Forestry, USDA Forest Service (Research Support Budget Grant RPO # 680-05: 'The catalytic effect of tree plantings on the rehabilitation of native forest biodiversity on degraded tropical lands'). The authors thank Mineração Rio do Norte for permitting access to the reforestation area for research purposes and offer special thanks to Sr Pedro Ferreira for his special expertise and assistance in identifying trees and seedlings in the field. The authors also thank Daniel Janzen and an anonymous reviewer for their helpful comments and suggestions on an earlier version of this paper.

## References

Aide, T.M., Zimmerman, J.K., Herrara, L., Rosario, M., 1995. Forest recovery in abandoned tropical pastures in Puerto Rico. For. Ecol. Manage. 77, 77–86.

Bradshaw, A.D., 1987. The reclamation of derelict land and the ecology of ecosystems. In: Jordan, W.R., Gilpin, M.E., Aber, J.D. (Eds.), Restoration Ecology: a Synthetic Approach to Ecological Research. Cambridge University Press, Cambridge, pp. 53–74.

Bradshaw, A., 1997. Restoration of mined lands — using natural processes. Ecol. Eng. 8, 255–269.

Dobson, A.P., Bradshaw, A.D., Baker, A.J.M., 1997. Hopes for the future: restoration ecology and conservation biology. Science 277, 515–522.

Ferraz, J.B.S., 1993. Soil factors influencing the reforestation on mining sites in Amazonia. In: Lieth, H., Lohmann, M. (Eds.), Restoration of Tropical Forest Ecosystems. Kluwer Academic, Dordrecht, pp. 47–52.

Fox, J.E.D., 1984. Rehabilitation of mined lands. For. Abstr. 45, 565–600.

Gaunt, R.J., Bliss, N.W., 1993. Bauxite mine rehabilitation at Trombetas in the Amazon Basin, Minerals Industry International. IMM Bull. 1011, 21–26.

Grant, C.D., Bell, D.T., Koch, J.M., Loneragan, W.A., 1996. Implications of seedling emergence to site restoration following bauxite mining in western Australia. Rest. Ecol. 4, 146–154.

Knowles, O.H., Parrotta, J.A., 1995. Amazonian forest restoration: an innovative system for native species selection based on phenological data and performance indices. Commun. For. Rev. 74, 230–243.

Knowles, O.H., Parrotta, J.A., 1997. Phenological observations and tree seed characteristics in an equatorial moist forest at Trombetas, Pará State, Brazil. In: Lieth, H., Schwartz, M.D. (Eds.), Phenology in Seasonal Climates I. Backhuys, Leiden, pp. 67–84.

Majer, J.D., 1992. Ant recolonisation of rehabilitated bauxite mines of Poços de Caldas, Brazil. J. Trop. Ecol. 8, 97–108.

Majer, J.D., 1996. Ant recolonization of rehabilitated bauxite mines at Trombetas, Pará, Brazil. J. Trop. Ecol. 12, 257–273.

Nepstad, D., Uhl, C., Serrão, E.A., 1991. Recuperation of a degraded Amazonian landscape: forest recovery and agricultural restoration. Ambio 20, 248–255.

Parrotta, J.A., 1993. Secondary forest regeneration on degraded tropical lands: the role of plantations as 'foster ecosystems'. In: Lieth, H., Lohmann, M. (Eds.), Restoration of Tropical Forest Ecosystems. Kluwer Academic, Dordrecht, pp. 63–73.

Parrotta, J.A., Knowles, O.H., 1999. Restoration of tropical moist forests on bauxite mined lands in the Brazilian Amazon. Rest. Ecol. 7, 103–116.

Parrotta, J.A., Knowles, O.H., Wunderle, J.M., Jr, 1997. Development of floristic diversity in 10-year-old restoration forests on a bauxite mined site in Amazonia. For. Ecol. Manage. 99, 21–42.

Pedreira Gonzaga, L.A., 1991. Levantamento da avifauna na área de influencia da Mineracão Rio do Norte S/A-Porto Trombetas, Pará. Internal Document. Mineração Rio do Norte, Trombetas, Pará, Brazil, 32 pp.

Tacey, W.H., 1979. Landscaping and revegetation practices used in rehabilitation after bauxite mining in western Australia. Reclam. Rev. 2, 123–132.

Tacey, W.H., Glossop, B.L., 1980. Assessment of topsoil handling techniques for the rehabilitation of sites mined for bauxite within the jarrah forest of western Australia. J. Appl. Ecol. 17, 195–201.

Uhl, C., Jordan, C.F., 1984. Succession and nutrient dynamics following forest cutting and burning in Amazonia. Ecology 65, 1476–1490.

Uhl, C., Buschbacher, R., Serrão, E.A.S., 1988. Abandoned pastures in eastern Amazonia. I. Patterns of plant succession. J. Ecol. 76, 663–681.

Wunderle, J.M., Jr, 1997. The role of animal seed dispersal in accelerating native forest regeneration on degraded tropical lands. For. Ecol. Manage. 99, 223–235.