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Forest Ecology and Management 152 (2001) 169–181

Forest Ecology and Management

www.elsevier.com/locate/foreco

An evaluation of direct seeding for reforestation of degraded lands in central São Paulo state, Brazil

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Received 7 June 2000; accepted 2 September 2000

Abstract

As part of a larger study evaluating several silvicultural techniques for restoring tropical moist forests on abandoned agricultural lands in southeastern Brazil, direct seeding with five early-successional Atlantic forest species was tested at three degraded sites, characterized by different soil types and land-use histories, within the Environmental Protection Area at Botucatu, SP. The species used in this study were *Chorisia speciosa*, *Croton floribundus, Enterolobium contorstisiliquum*, *Mimosa scabrella*, and *Schizolobium parahyba*. Scarified seeds of each of these species were sown in prepared seed spots in replicated, 0.25 ha mixed-species plots at an initial espacement of 1 m $\times$ 1 m at each site. Of the five species planted, only two, *Enterolobium* and *Schizolobium*, showed good seed germination, seedling survival, and early growth rates, averaging 4.1–4.6 cm stem diameter and 1.5–1.7 m height growth during the first 2 years after sowing. These two species constituted 88–100% of the total stand density, which ranged from 1050 to 1790 stems ha^{-1} at 2 years. Despite the poor performance of the other species tested, we observed that the natural regeneration of native forest species originating from remnant forests in the general vicinity of our study sites was significantly greater within the direct-seeded plots than in unplanted control plots that were protected from fire and other disturbances. Published by Elsevier Science B.V.

Keywords: Forest restoration; Native species; Natural regeneration; Seedling growth; Tropics

1. Introduction

The Atlantic forest formation in Brazil, which includes dense evergreen forests, semideciduous seasonal forests and gallery forests, is one of the worlds's greatest centers of tropical biodiversity as well as one of the most threatened by deforestation and degradation (Fundação SOS Mata Atlântica, 1992; Bryant et al., 1997). These forests formerly occupied a large area of eastern Brazil from Bahia to Rio Grande do Norte (Cámara, 1991). This region, home to an estimated 70% of Brazil's total population of 150 million, has a long history of deforestation and soil resource degradation associated with numerous cycles of agricultural development in Brazil since the colonial era. Today, the total area of native forests is estimated at less than 10% of its original extent (Fundação SOS Mata Atlântica/INPE, 1993). Outside of protected conservation areas, most remaining forest fragments are disturbed with respect to their structure and function, and are under constant threat from fire and other human disturbances. Current environmental

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0378-1127/01/$ – see front matter. Published by Elsevier Science B.V.
PII: S0378-1127(00)00600-9

legislation in Brazil aimed at reversing deforestation trends and protecting the region's agricultural soils, rivers, and their hydroelectric generation capacity, requires protection of remaining natural forests in this region and the restoration of forests on 20% of the total land area on all rural properties, particularly in riparian sites. However, the owners of small- and medium-sized land holdings, who generally have severely limited financial resources, rarely participate in environmental rehabilitation projects due to their high costs and lack of direct financial returns.

A proportion of the deforested lands in the Atlantic forest region can and should be rehabilitated for agricultural production. However, there are significant areas of degraded, agriculturally marginal lands that cannot be economically rehabilitated for either agricultural or intensive commercial forestry production in the near term, as well as lands of high potential value for conservation and watershed protection. These include degraded rangelands and pastures, riparian areas, steep slopes subject to severe erosion, or sites that could serve as corridors linking forest fragments of high biodiversity value. While some of these lands in the vicinity of remnant native forests would naturally revert fairly quickly to secondary forest if the pressures on them such as fire and livestock grazing were reduced, other more isolated or severely degraded sites will require some form of management to facilitate their recovery. There is a need to develop techniques for native forest restoration in this region that are inexpensive to implement and provide some level of direct, short-term economic return to farmers and other landholders.

Forest plantings can play a key role in harmonizing long-term forest ecosystem rehabilitation (or restoration) goals with near-term socio-economic development objectives (Brown and Lugo, 1994; Lamb and Tomlinson, 1994). Recent studies have shown that plantations established for the production of timber and other forest products can facilitate, or "catalyze" native forest succession in their understories on sites where persistent ecological barriers to succession would otherwise prelude recolonization and enrichment by native forest species (see, for example Soni et al., 1989; Lübbe and Geldenhuys, 1991; Lugo, 1992; Lugo et al., 1993; Parrotta, 1992, 1993, 1995, 1999; Mitra and Sheldon, 1993; Kuusipalo et al., 1995; Lamb et al., 1997; Parrotta and Turnbull, 1997; Lamb, 1998; Parrotta and Knowles, 1999). Such studies have shown that the changes in understory microclimate, increased vegetation structural complexity and habitat diversity, and the development of litter and humus layers that occur during the early years of plantation growth often result in increased seed inputs from neighboring native forests (by seed dispersing wildlife attracted to the plantations), suppression of competing grasses, and alterations in microclimatic conditions that favor seedling survival and growth. In the absence of silvicultural management aimed at eliminating woody understory regeneration, the plantation system is replaced by a mixed forest comprised of the planted species and an increasing number of early and late successional tree species and other floristic elements drawn from surrounding forest areas.

To date, most of the silvicultural approaches developed in this region for forest restoration have not been applied beyond an experimental scale, and those that have been used over larger areas (by mining and hydroelectric companies) have a limited applicability for most landholders due to their high establishment and maintenance costs (Maschio et al., 1992; Kageyama et al., 1994). In 1997–1998 a research project was established at three contrasting degraded sites in the Environmental Protection Area at Botucatu in São Paulo State, Brazil to evaluate financial costs and benefits, productivity and ecological impact of four different silvicultural techniques for forest rehabilitation that can be easily adopted by private small- and medium-sized landowners in the region. The objectives of this project are to evaluate the ecological impact and the economic viability of several plantation models utilizing a total of 47 native tree species for restoring seasonal, semideciduous Atlantic forests under different site conditions (variable soil fertility and landscape floristic patterns) and management regimes. Specific objectives include the evaluation of: the adaptability and productivity of native Atlantic forest species on deforested sites characterized by different levels of soil degradation; the effects of these management systems on soil productivity and belowground ecological processes; patterns of natural regeneration and development of plant and animal species diversity; and the financial costs and benefits associated with each model, or treatment.

One of the treatments included in this experiment is direct seeding using five quick-growing, early successional, native tree species established in mixed-species plantation blocks. The potential advantages of direct seeding over other plantation establishment techniques (i.e. planting of nursery-grown seedlings, wildlings or rooted cuttings) include cost savings associated with nursery care and planting, as well as the possibility that trees established by this means may develop more naturally, and quickly, than would transplanted seedlings or cuttings. There are, however, significant disadvantages of direct seeding that usually outweigh these advantages, i.e. typically very low germination survival percentages resulting in either inadequate plantation stocking and/or increased seed costs to compensate for poor germination and survival, poor early seedling growth relative to nursery-grown seedlings that receive daily care, and increased seedling mortality associated with weed competition (or increased weeding costs to overcome this) in addition to increased susceptibility to poor weather conditions (Evans, 1982). While direct seeding failures (rarely reported in the literature) greatly outnumber successes, it has been successfully used in many parts of the world for establishment of tree crops such as *Acacia*, *Anacardium occidentale*, *Azadirachta indica*, *Gmelina arborea*, *Swietenia*, and *Pinus* in commercial plantations, and for numerous other tropical/subtropical species in non-commercial plantations established for various environmental rehabilitation purposes (Laurie, 1974; Evans, 1982; Barbosa and Barbosa, 1992; Francis, 1993; Knowles and Parrotta, 1995; Sun et al., 1995; Sun and Dickinson, 1995, 1996; Fernandes et al., 1998; Parrotta and Knowles, 1999). Despite generally rather poor record to date, we feel that the potential cost savings associated with direct seeding, particularly for species whose seeds are readily available and amenable to this method of establishment, could outweigh its disadvantages and offer a more economical means for reestablishing forest cover over large areas of degraded lands (Thomson, 1992; Applegate et al., 1993). What is required is a more systematic screening of potential species and their response to direct seeding under field conditions, and evaluations of costs associated with plantation establishment and aftercare relative to those of more commonly used planting stock such as nursery-grown seedlings.

In this paper, we present the early results of our experiments with direct seeding at three contrasting sites. Specifically, we examine the financial costs for establishment and maintenance, seed germination rates, survival and tree growth during the first 2 years after establishment, and patterns of natural regeneration by within plantation plots compared to unplanted control plots.

2. Materials and methods

2.1. Site description

The study sites are located on two adjacent properties (Fazenda Lageado, Fazenda Edgardia: Fig. 1) within the campus of the State University of São Paulo at Botucatu (UNESP-FCA) in the south-central region of São Paulo State (22°50′S; 48°24′W). The natural vegetation in this area is classified as seasonal semi-deciduous tropical forest. The experimental sites receive an average annual rainfall of 1300 mm, mostly between the months of October and March. The mean annual temperature is 19.4°C, with monthly means ranging from 16.3°C in July to 21.9°C in January. The local topography is hilly, with elevations ranging from 464 to 775 m. Due to a high degree of geologic and topographic variability, soils at these sites are also variable, ranging from fertile clays of basaltic origin to nutrient-poor, acidic sands (Table 1).

Site 1 (Fazenda Lageado) is located at 700 m elevation in an area with red clay (''terra roxa'') soils of optimal fertility and good physical properties but with a tendency towards compaction. Prior to installation of the experiment the vegetation on this abandoned pasture site was dominated by very tall (2–3 m) grasses (principally Napier grass, *Pennisetum purpureum*) and pasture herbs. This site is situated near the Ribeirão Lavapés ravine in a relatively isolated valley surrounded by agricultural fields. Riparian forest fragments are present approximately 200 m downslope from the experiment site towards the river. Site 2 (Fazenda Edgardia) is located at 574 m elevation in an area with red-yellow podzolic soils of medium fertility. In recent decades the site was used as a *Citrus* orchard. It is located approximately 50 m from a forest remnant in a good state of conservation. The ground cover is dominated by grasses, mainly *Brachiaria*

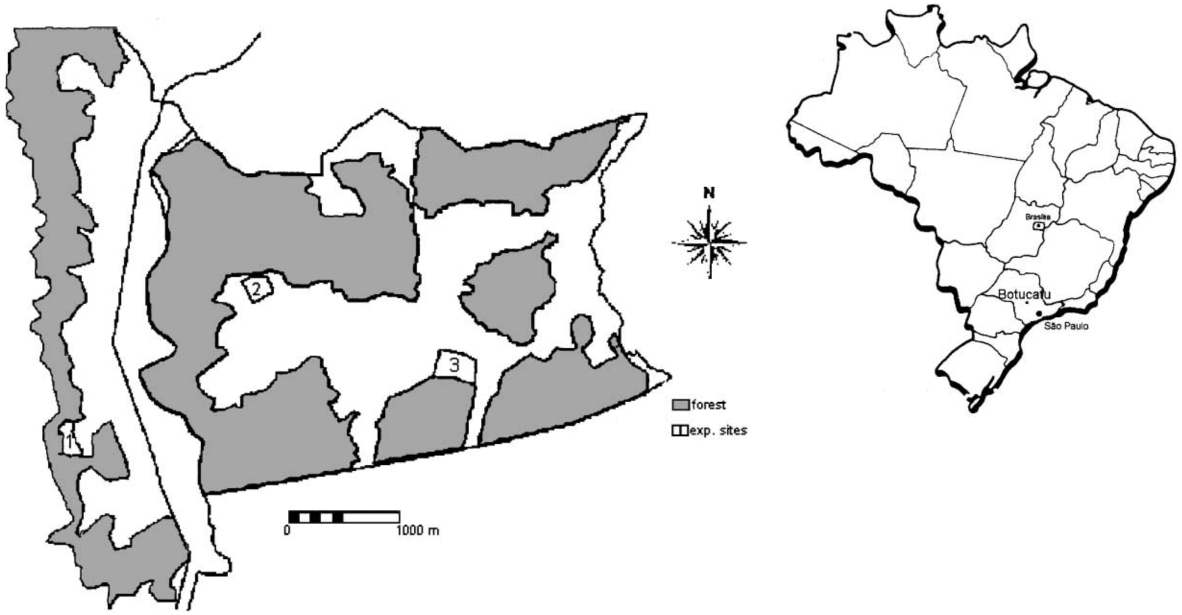

Fig. 1. Location of study sites at the Fazenda Lageado (Site 1) and Fazenda Edgardia (Sites 2 and 3), State University of São Paulo at Botucatu (UNESP-FCA), São Paulo, Brazil.

decumbens. Site 3 (Fazenda Edgardia) is located at 540 m elevation in an area with moderately acidic and leached quartz sand soils of very low fertility and subject to severe erosion. The site was formerly used (for several decades) as a pecan and mango orchard; many of these now senescent trees remain in the vicinity of experimental plots. Most recently, the area has been used for livestock grazing and is

Table 1
Physical and chemical properties of soils at study sites, 0–20 cm depth[a]

	Site 1	Site 2	Site 3
Soil texture[b]	Clay	Loamy sand	Sand/loamy sand
Bulk density (g/cm^3)	1.37	1.55	1.52
pH[c]	5.3	4.8	4.5
Organic matter[d] (%)	1.99	0.64	0.67
N (%)	0.155	0.06	0.048
Exchangeable ions[e] ($mmol/1000\ cm^3$)			
$P_{extractable}$[e] ($mg/1000\ cm^3$)	9.3	8.1	2.3
K	3.1	1.2	1.3
Ca	46.5	10.7	7.0
Mg	14.9	4.5	2.5
Acidity (H + Al)	32.8	20.4	18.5
Cation exchange capacity$_{K+Ca+Mg+H+Al}$	97.1	36.8	29.4
Base saturation (%)	66.4	44.6	36.7

[a] Average values for all plots at each site ($n = 15$/site).
[b] USDA classification system.
[c] Determined in 0.01 N $CaCl_2$ (Raij and van Quaggio, 1983).
[d] % Organic carbon $\times$ 1.75 (Camargo et al., 1986).
[e] Ion exchange resin extraction (Camargo et al., 1986).

dominated by "colonião" grass (*Panicum maximum*) and *B. decumbens*. This site is located approximately 50–100 m from a secondary forest fragment which has been degraded by fire and wood extraction in the recent past.

2.2. Experimental design

At each site, a set of fifteen 0.25 ha (50 m $\times$ 50 m) experimental plots were established using a randomized complete block design, with three replications each of the following five treatments: (1) an unplanted control; (2) direct seeding of five fast-growing early-successional species using minimal tillage practices; (3) a modified taungya (agroforestry) system involving mixed-species line plantings of 22 fast-growing fuelwood and slower-growing timber species, interplanted with annual crops during the first 2–4 years; and (4) a mixture of 27 multi-purpose and commercial timber species; and (5) restoration plantings of 40 native forest species, including early-fruiting understory species.

In the direct seeding treatment, five early successional, secondary forest species were chosen for study, based on their ecological and silvicultural characteristics (including availability of seed local forests or commercial sources and ease of propagation) and inferences on their adaptability to study site conditions. These species are:

- *Chorisia speciosa* St. Hil (local name "paineira": family Bombacaceae), a deciduous forest gap species up to 30 m tall;
- *Croton floribundus* Spreng ("capixingui": Euphorbiaceae), a deciduous or semideciduous pioneer attaining heights of 6–10 m;
- *Enterolobium contortisiliquum* (Vell.) Morong. ("timboril": Leguminosae, Mimosoideae), a pioneer species 20–35 m tall at maturity;
- *Mimosa scabrella* Benth. ("bracatinga": Leguminosae, Mimosoideae), a semidiciduous pioneer up to 15 m tall; and,
- *Schizolobium parahyba* ("guapuruvu": Leguminosae, Papilionoideae), a deciduous pioneer species found exclusively in the Atlantic forest region and typically in riparian forests (Lorenzi, 1992).

With the exception of *M. scabrella*, whose seeds were obtained from EMBRAPA's National Center for Forestry Research in Curitiba, Paraná State, the seed sources for all other species were purchased from various locations within São Paulo State through the Forestry Institute of São Paulo. Prior to planting, appropriate seed treatments were applied to break dormancy: for *Chorisia*, *Croton* and *Enterolobium*, seeds were soaked in water at room temperature for 12 h immediately prior to sowing; for *Mimosa* and *Schizolobium*, seeds were immersed in hot water (80°C) for 2 min followed by soaking in water at room temperature for 12 h. Germination tests were conducted in the nursery for comparison with germination data obtained in the field. Seeds were sown in groups of 1–6 per planting spot (depending on species) at approximately 5 cm depth in prepared lines located along slope contours. Each line was planted with a single species, with a 1 m spacing between planting spots and between lines, and each plot (at all sites) included the same sequence of species in successive lines.

2.3. Site preparation, planting and maintenance

Experimental plots at each site were fenced to provide protection against grazing, and fire lines established around the periphery of the fences enclosing each experimental area. Prior to planting, a post-emergent herbicide (glyphosate) was applied to all treatment and control plots to suppress grasses; at Site 1, the exuberant *P. purpureum* growth required rototilling in advance of herbicide application. During the first 2 years, additional spot applications of this herbicide were used, in addition to manual weeding as required around seedlings to ensure seedling survival and good early growth. Ant traps containing a formicide (Myrex^{TM}, active ingredient sulfluoramide) were set up at selected spots within the plantations to reduce herbivory damage to seedlings. Planting lines were prepared (to a depth of 40 cm) using a subsoiler pulled by a tractor, a practice commonly used in minimal tillage agriculture and commercial forestry in this region. Planting was carried out in early 1997 during the wet season (March).

2.4. Data collection and analysis

Seed germination and seedling survival were evaluated 1.5 and 24 months, respectively, after planting.

Stem basal diameters (at 5 cm above the root collar) and tree heights were measured were recorded for all trees in each plot at 24 months. The species composition of the soil seed bank was characterized indirectly at the start of the experiment by identifying and enumerating all plants in five randomly located 1 m × 1 m quadrats in each of the study plots 60 days after site preparation (and post-emergent herbicide application). Approximately 2.5 years after planting, all woody plants (trees and shrubs) that had regenerated naturally (i.e. those not planted) since plot establishment were identified and enumerated in the direct seeding and control plots.

Operational costs and labor requirements (worker hours) for activities related to plantation establishment and maintenance were recorded during throughout the study period. These included all material, machinery and labor costs associated with production of planting material (cost of seeds and nursery treatments), site preparation (roto-tilling and deep-ripping, herbicide application), plantation establishment (seed sowing), and maintenance (manual weeding, herbicide and formicide application). These data were used to calculate the initial (first 2 years) plantation costs at each site on a per-hectare basis.

Analyses of variance (ANOVA) were used to compare seed germination, seedling survival and tree growth data for each species among sites. Germination percentage data were arcsin square-root transformed prior to analysis (Mead and Curnow, 1983). Bonferroni's least significant difference (LSD) procedure was used to separate the means of dependent variables that were significantly affected by site.

Table 2
Establishment and maintenance costs for direct seeding through first 2 years of study[a]

	US$/ha		
	Site 1	Site 2	Site 3
Establishment costs			
Roto-tilling	86	0	0
Subsoiling	31	31	31
Herbicide	20	20	20
Herbicide application	78	59	59
Formicide	21	26	21
Formicide application	9	9	9
Irrigation	29	29	29
Seeds	182	182	182
Manual seeding	164	117	117
Subtotal	$620	$473	$468
Maintenance costs (year 1)			
Manual weeding	53	35	35
Herbicide	37	37	37
Herbicide application	35	35	35
Formicide	21	21	21
Formicide application	9	9	9
Subtotal	$155	$137	$137
Maintenance costs (year 2)			
Manual weeding	35	35	35
Herbicide	37	37	37
Herbicide application	35	35	35
Formicide	21	21	21
Formicide application	9	9	9
Subtotal	$137	$137	$137
Total costs	$912	$747	$742

[a] During the period of study, 1US$ = Reis 1.70; manual labor costs averaged \$8.80 per day (8 h); costs for mechanical site preparation and herbicide application averaged \$16.65–\$17.65 per day; herbicide and formicide material costs averaged \$5.30/l and \$5.30/kg, respectively.

3. Results and discussion

3.1. Plantation costs

The establishment and maintenance costs during the 2-year study period ranged from \$747 (at Sites 2 and 3) to \$912 (at Site 1) per hectare (Table 2). Establishment costs constituted 63–68% of the total costs; seeds (\$182 ha^{-1}) and sowing activities (\$117–164 ha^{-1}) were the most costly operations. Establishment costs were approximately \$150 higher for Site 1 than for the other two sites, due to the need to physically suppress the dominant Napier grass (*P. purpureum*) at this site by roto-tilling prior to herbicide application, and the higher costs of manual seeding. Maintenance costs (for manual weeding, herbicide and formicide applications) were \$137–155 ha^{-1} during the first year (higher at Site 1 due to higher manual weeding requirements) and \$137 ha^{-1} for all sites during the second year.

These costs compare favorably with those for plantation establishment and maintenance at this site using nursery-grown seedlings of native tree species in other plantation treatments included in this project, which averaged \$1200–2500 ha^{-1} (unpublished data).

Table 3
Seed germination, seedling survival and early growth in direct sowing treatments[a]

	Site 1	Site 2	Site 3	All sites	ANOVA[b]
Percent seed germination[c]					
Chorisia speciosa	13.1 ± 1.8a	5.1 ± 1.9b	4.5 ± 1.4b	7.6	*
Croton floribundus	0	0	0	0	ns
Enterolobium contorstisiliquum	18.1 ± 4.4	20.8 ± 1.8	18.7 ± 1.8	19.2	ns
Mimosa scabrella	3.3 ± 1.7	0.5 ± 0.5	0	1.3	ns
Schizolobium parahyba	18.8 ± 5.3	21.6 ± 2.3	30.6 ± 13.0	23.7	ns
All species	10.6 ± 1.5	9.6 ± 1.0	10.8 ± 2.9	10.3	ns
Stand density at 45 days (No./ha)[d]					
Chorisia speciosa	752 ± 171	344 ± 110	308 ± 97	468	ns
Croton floribundus	0	0	0	0	ns
Enterolobium contorstisiliquum	924 ± 153	1209 ± 49	1009 ± 127	1047	ns
Mimosa scabrella	268 ± 135	39 ± 39	0	102	ns
Schizolobium parahyba	564 ± 150	540 ± 42	611 ± 256	572	ns
All species	2508 ± 233	2132 ± 200	1928 ± 330	2189	ns
Stand density at 2 years (No./ha)[d]					
Chorisia speciosa	136 ± 89	1 ± 1	0	46	ns
Croton floribundus	20 ± 20	0	5 ± 5	8	ns
Enterolobium contorstisiliquum	992 ± 259	1291 ± 289	613 ± 200	965	ns
Mimosa scabrella	25 ± 13	0	0	8	ns
Schizolobium parahyba	365 ± 99	495 ± 145	433 ± 229	431	ns
All species	1538 ± 395	1787 ± 402	1051 ± 174	1459	ns
Tree height (m)					
Chorisia speciosa	0.4 ± 0.3	0.1 ± 0.1	0	0.2	ns
Croton floribundus	1.0 ± 1.0	0	0.5 ± 0.5	0.5	ns
Enterolobium contorstisiliquum	1.6 ± 0.2a	2.2 ± 0.2a	0.8 ± 0.1b	1.5	*
Mimosa scabrella	1.3 ± 1.0	0	0	0.4	ns
Schizolobium parahyba	2.0 ± 0.4	1.4 ± 0.02	1.8 ± 0.4	1.7	ns
Stem basal diameter (cm)					
Chorisia speciosa	1.2 ± 0.8	0.4 ± 0.4	0	0.5	ns
Croton floribundus	1.4 ± 1.4	0	0.1 ± 0.1	0.5	ns
Enterolobium contorstisiliquum	4.1 ± 0.4ab	6.5 ± 1.2a	1.8 ± 0.3b	4.1	*
Mimosa scabrella	1.9 ± 1.0	0	0	0.6	ns
Schizolobium parahyba	4.5 ± 1.2	4.8 ± 0.6	4.6 ± 0.7	4.6	ns

[a] Values represent means of replicate plot averages at each site ± standard error ($n = 3$); zeros indicate 100% mortality in all three replicate plots at each site.
[b] ANOVA results: ns — site effect not significant; $^*P < 0.05$, similar letters within a row indicate that means were similar ($P < 0.05$; LSD, *t*-test).
[c] Based on total number of seeds sown in each plot, 45 days after sowing.
[d] Based on the number of planting spots with one or more surviving seedlings/trees at 45 days or 2 years after sowing.

Establishment and early maintenance costs for commercial *Eucalyptus* plantations average \$700 ha^{-1}.

3.2. Germination rates and seedling survival

Seed germination and survival varied considerably among species and, for one species (*C. speciosa*), between sites (Table 3). Forty-five days after sowing, average germination rates across all sites ranged from 19–24% for *Enterolobium contorstisiliquum* and *S. parahyba* to less than 1.3% for *C. floribundus* and *M. scabrella*; for these four species, there were no significant site effects (ANOVA, $P < 0.05$). Intermediate germination rates were observed for *C. speciosa* (4.5–13.1%), and were significantly higher at Site 1 than at Site 2 or 3. These values were much lower than those obtained in nursery trials, in which germination percentages for *Croton* averated 35% up to 90 days after sowing, and those of the other four species exceeded 70%.

Despite the very low germination and 45-day survival rates for three of the five species used in this study, the resultant stand densities (numbers of planting spots per hectare with one or more surviving seedings 45 days after sowing) was reasonably high at all sites, ranging from a mean of 1928 ± 330 (at Site 3) to 2508 ± 233 (at Site 1). Subsequent mortality up to 2 years after sowing was severe for *Chorisia* (82% at Site 1 to 100% at Sites 2 and 3) and *Mimosa* (91–100% across sites) but low for both *Enterolobium* (averaging 7.8% for all sites) and *Schizolobium* (24.7% for all sites). As a result, after 2 years stand densities averaged 1538, 1787, and 1051 ha^{-1}, respectively, for Sites 1, 2 and 3, and were composed almost exclusively of *Enterolobium* (58–65% among sites) and *Schizolobium* (24–41% among sites).

The low initial survival and subsequent mortality rates for three of the five species tested in this study can be attributed to several factors. First, sub-optimal seed quality may have been a problem, the seeds having been collected from parent trees in a variety of locations within the region that may or may not have been similar to study site conditions. Furthermore, in the case of *M. scabrella* seeds, despite fairly high germination percentages (>70%) obtained in nursery tests, early seedling mortality in the nursery was very high, indicating that these seeds were of poor quality and probably more than 1 year old. A second factor was insufficient rainfall during the days immediately after sowing: having broken seed dormancy by pre-treatment immediately prior to planting, this resulted in desiccation and mortality of germinating seeds. This effect was particularly marked in *M. scabrella*. Given these problems, it is strongly recommended that future plantation establishment efforts by direct seeding pay close attention to seed quality, using fresh seeds collected from several parent trees growing on sites where soils and climatic conditions are broadly similar to those being reforested, and that planting be carried out during periods of expected high rainfall. A third factor that contributed to seedling mortality in *Chorisia*, but probably not the other four species, was competition with grasses; while the early growth of this species is usually rapid, it is highly sensitive to competition at the seedling stage, and requires frequent weeding in its immediate vicinity during the early growth phase.

3.3. Tree growth

During the first 2 years after sowing, height and stem diameter growth rates differed greatly among species, with differences among species broadly paralleling those for seed germination and seedling survival (Table 3). For *Chorisia*, *Croton*, and *Mimosa*, average heights (for the few surviving seedlings) at 2 years were 0.16, 0.50 and 0.43 cm, respectively; the corresponding average stem basal diameters at this age were 0.53, 0.50 and 0.63 cm. Although site differences were not significant for these growth parameters (ANOVA, $P < 0.05$), there was a trend towards higher growth rates at Site 1 than at other sites for *Chorisia* and *Croton* (survival was zero for *Mimosa* at Sites 2 and 3). Of the two more successful species, *Enterolobium* height and stem diameter growth averaged 1.5 m and 4.1 cm, respectively, across all sites at 2 years; its growth was significantly greater at Site 2 (2.2 m, 6.5 cm) than at either Site 1 (1.6 m, 4.1 cm) or Site 3 (0.8 m, 1.8 cm). *Schizolobium* growth rates were similar across sites and slightly higher than those for *Enterolobium*, averaging 1.4–2.0 m in height and 4.5–4.8 cm in stem diameter at 2 years. It appears that both of these species, in addition to being well-suited to establishment in grass-dominated habitats in this region by direct seeding, are adapted to the broad range of site conditions, especially soil physical and chemical properties, included in this study (Table 1). As discussed earlier, there are clearly problems associated with the direct seeding techniques employed for the remaining three species tested in this study which remain to be resolved.

3.4. Natural regeneration

At the time of plantation establishment, the soil seed bank at the three experimental sites was comprised exclusively of herbaceous species. These included six grass species and 53 species representing 18 other families (Table 4). Species richness (total number of species at each site) was greater at Site 1 (55 species) than at Site 2 (48 species) and Site 3 (31 species). The density of plants regenerating from

Table 4
Composition of viable soil seed bank in experimental areas at time of plantation establishment[a]

Family	Scientific name	Common name	Sites where present		
			1	2	3
Acanthaceae	*Thunbergia alata*	Amarelinha	x		
Amaranthaceae	*Alternanthera brasiliana*	Sempre viva	x	x	
	Alternanthera tenella colla	Apaga fogo	x	x	x
	Amaranthus hybridus	Caruru crista de galo	x	x	x
	Amaranthus viridis	Caruru verde	x	x	x
Apiaceae	*Bowlesia incana*	Erva salsa	x	x	
Comelinaceae	*Commelina virginica*	Trapoeraba	x	x	x
Compositae	*Artemisia* sp.	Losna	x	x	x
	Bidens pillosa	Picão preto	x	x	x
	Conyza bonariensis	Rabo de foguete	x	x	x
	Eclipta alla	Lanceta	x		
	Emilia sonchifolia	Pincel	x	x	x
	Galinsoga parviflora	Botão de ouro	x	x	
	Senecio brasiliensis	Berneira	x	x	
	Sonchus oleraceus	Serralha	x	x	x
	Xanthium cavallinesii	Carrapicho-bravo	x	x	x
Convolvulaceae	*Ipomoea acuminata*	Campainha	x		
	Ipomoea purpurea	Campainha	x		
	Ipomoea quamoclit	Cipó esqueleto	x		
	Ipomoea grandifolia	Campainha	x		
Cruciferae	*Raphanus* sp.	Nabiça	x	x	
Cucurbitaceae	*Momordica charantia*	Melão S.Caetano		x	
Cyperaceae	*Cyperus esculentus*	Tiriricão		x	x
	Cyperus ferax	Chufa	x		
	Cyperus iria	Tiririca	x	x	x
Euphorbiaceae	*Chamaesyce hirta*	Erva S. Luzia	x	x	
	Euphorbia heterophylla	Leiteria	x	x	x
	Euphobia prostrata	Quebra pedra	x	x	x
	Phyllanthus corcovadensis	Quebra pedra	x	x	x
	Phyllanthus tenellus	Quebra pedra	x	x	x
	Ricinus communis	Mamona	x	x	x
Gramineae	*Brachiaria decumbens*	Braquiária	x	x	x
	Brachiaria mutica	Capim Angola	x		
	Cenchrus echinatus	Capim carrapicho	x	x	x
	Panicum maximum	Colonião	x	x	x
	Rhynchelytrum repens	Capim favorito	x	x	x
	Setaria geniculata	Capim rabo de gato	x	x	
Labiatae	*Leonotis nepetaefolia*	Cordão de frade	x		
	Leonurus sibiricus	Rubim	x	x	x
Leguminosae (Caesalpinioideae)	*Cassia patellaria*	Peninha	x	x	
	Indigofera hirsuta	Anil	x		
	Indigofera suffruticosa	Anileira	x	x	x
	Senna obtusifolia	Fedegoso	x	x	
	Senna occidentalis	Fedegoso	x	x	x

Table 4 (*Continued*)

Family	Scientific name	Common name	Sites where present		
			1	2	3
Leguminosae (Papilionoideae)	*Crotalaria lanceolata*	Guizo de cobra	x	x	x
	Crotalaria pallida	Guizo de cobra	x	x	x
Malvaceae	*Malvastrum coromandelianum*	Guanxuma	x	x	
	Sida glaziovii	Guanxuma branca	x	x	
	Sida urens	Guanxuma dourada	x	x	
	Sidastrum micranthum	Malva	x	x	
Portulacaceae	*Portulaca oleracea*	Beldroega	x	x	
	Talinum patens	Maria gorda	x	x	x
Rubiaceae	*Diodia teres*	Mata pasto	x	x	x
Solanaceae	*Solanum aculeatissimum*	Arrebenta cavalo	x	x	x
	Solanum americanum	Maria pretinha	x	x	x
	Solanum sisymbriifolium	Juá	x	x	x
Sterculiaceae	*Waltheria americana*	Malva veludo	x	x	
Verbenaceae	*Latana camara*	Cambará de espinho		x	

[a] Based on surveys of regeneration in all experimental plots 60 days after site preparation.

the soil seed bank 60 days after post-emergent herbicide application was 110 m^{-2} at Site 1, 75 m^{-2} at Site 2, and 50 m^{-2} at Site 3. Grasses comprised an average of 83% of the regeneration (individuals m^{-2}) at Site 1, 52% at Site 2, and only 15% of the total at Site 3.

Approximately 2.5 years after planting, natural regeneration of woody perennial species was observed at all sites in both the direct-seeding and unplanted control plots (treatments). This included species with wind-dispersed seeds, as well as those whose seeds are typically dispersed by birds and/or bats (Table 5). The majority are shrubs and tree species very commonly found in early successional forests in this region. The number and composition of regenerating woody species varied considerably among sites and between treatments at each site. Inter-site differences can be attributed to differences in the floristic composition of forest fragments in close proximity to the study areas and other seed sources (remnant trees) located within the study areas (such as guava — *Psidium guajava* — present at Site 2). Within-site treatment differences in woody species composition did not follow any clear patterns with respect to modes of seed dispersal; both direct-seeded and control plots included similar proportions of woody species dispersed by wind and fauna.

Naturally regenerating woody species richness was significantly higher in the direct seeding treatment than in the unplanted control areas (treatment means: 6.1 versus 2.8 species/plot; $P < 0.05$, ANOVA). Although the density of regenerating woody species in the direct-seeded plots was generally much higher than in the control plots (treatment means: 316 versus 167 ha^{-1}), these differences were not statistically significant. These data strongly suggest that while natural regeneration of woody perennial species is occurring in unplanted plots protected from fire, grazing and other disturbances that can preclude or slow forest succession, the rates of woody species recolonization (both species richness and density) are enhanced in the (direct-seeded) plantations. This may be due to increased seed rain through the provision of perches for frugivorous birds and bats, and/or to improved understory microclimatic conditions and decreased grass competition beneath the planted trees that facilitate woody species seed germination and seedling growth. Given the fact that wind-dispersed species (which presumably arrive in both the direct-seeded and control plots at similar rates) are more abundant in terms of species richness and regeneration density in the direct-seeded plots, it would seem that at this stage of development at least, the increased

Table 5
Natural regeneration of tree and shrub species in direct seeding treatment and control plots

Species	Family	Local name	Seed dispersal vector	Number of individuals ha^{-1}					
				Direct seeding treatment			Control		
				Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Mangifera indica	Anacardiaceae	Manga	Fauna		0	4.0			
Schinus terebinthifolius	Anacardiaceae	Aroeira pimentiera	Fauna	1.3				2.7	
Peschiera fuchsiaefolia	Apocynaceae	Leiteira	Fauna	28.0	29.3	6.7	4.0	18.7	1.3
Syagrus oleraceae	Arecaceae	Coqueiro guariroba	Fauna			1.3			
Tecoma stans	Bignoniaceae	Ipê de jardim	Wind		2.7				
Carica papaya	Caricaceae	Mamão	Fauna	1.3					
Gochnatia polymorpha	Compositae	Cambará-guacu	Wind			9.3			
Vernonia polyanthes	Compositae	Assa peixe	Wind	1.3	46.7				
Croton urucurana	Euphorbiaceae	Capixingui	Fauna	41.3					
Nectandra megapotamica	Lauraceae	Canelinha	Fauna	1.3					
Peltophorum dubium	Leguminosae (C)	Canafistula	Wind	1.3	9.3				
Enterolobium contorstisiliquum	Leguminosae (M)	Timboril	Fauna					8.0	
Piptadenia gonoacantha	Leguminosae (M)	Pau jacaré	Wind	2.7					
Bauhinia forficata	Leguminosae (P)	Bauhinia	Wind	26.7	13.3				
Centrolobium tomentosum	Leguminosae (P)	Araribá	Wind	5.3					
Lonchocarpus muellbergianus	Leguminosae (P)	Embira de sapo	Wind	90.7			12.0	1.3	
Machaerium brasiliensis	Leguminosae (P)	Sapuvão	Wind				42.7		
Platypodium elegans	Leguminosae (P)	Amendoim campo	Wind	1.3		1.3		5.3	
Cedrela fissilis	Meliaceae	Cedro	Wind			1.3			
Psidium guajava L.	Myrtaceae	Goiaba	Fauna	4.0	332.0	30.7	2.7	349.3	4.0
Citrus sp.	Rutaceae	Limão	Fauna		25.1	2.7			
Solanum ciliatum	Solanaceae	Juá	Fauna			52.0			
Solanum erianthum	Solanaceae	Fumo bravo	Fauna	38.7		16.0	2.7		6.7
Solanum paniculatum	Solanaceae	Jurubeba	Fauna	26.7					
Aloysia virgata	Verbenaceae	Lixeira	Wind	37.3		1.3	17.3	4.0	1.3
Lantana camara	Verbenaceae	Cambará colorido	Fauna	2.7	48.0			16.0	
Lantana lilacina	Verbenaceae	Cambará roxo	Fauna	2.7					
Mean no. per ha ± S.E. ($n = 3$ plots/site)				245 ± 124	485 ± 159	217 ± 136	81 ± 69	405 ± 117	13 ± 7
Mean no. species per plot ± S.E. ($n = 3$)				6.7 ± 2.8	5.0 ± 0.6	6.7 ± 3.3	3.0 ± 1.0	3.7 ± 1.2	1.7 ± 0.7

regeneration rates observed in the planted plots are due mainly to the effects of the planted species on understory microclimatic conditions and partial suppression of competion by herbaceous species.

4. Conclusions

The results of this study show that direct seeding, despite its risks, can be successfully used as an alternative to more expensive (though generally less risky) methods of plantation establishment on grass-dominated, degraded tropical landscapes. Despite good site preparation, including initial suppression of competing herbaceous vegetation, timely planting, use of prepared sowing lines, and post-planting care (weeding), the poor performance of three of the five species used in this study highlighted the need for preliminary testing of species adaptability to direct-sowing under field conditions (*C. speciosa* and *C. floribundus* were clearly not suitable) and the need to use high-quality seeds for all species (in this study, a deficiency for *M. scabrella*). Adequate germination and seedling survival rates, as well as rapid growth in *E. contorstisiliquum* and *S. parahyba* during the first 2 years after sowing yielded developing forest stands that were adequately stocked (1000–1800 trees ha^{-1}) to facilitate natural regeneration by native woody shrub species in their understories.

Acknowledgements

We wish to thank Elder C. Matos, Maurício Scorsatto Sartori, Marcelo Zamboni Hildebrand, Ciro G.G. Croce, Julio C.R. Ferreira, Renato D. Lopes, and Cristina Silva Reis, Claudia Irene de Oliveira Rezende and Roberta Cristina Zumba for their invaluable assistance in the field. We also acknowledge Roberto Lyra Villas Bôas, Leonardo T. Büll, Helio Grassi and Maria Helena Moraes of the Natural Resources Department of UNESP/FCA for their help in soil analyses (data presented in Table 1), and Luís Alberto B. Jorge for his kind assistance in the preparation of the site map (Fig. 1). We thank A.E. Lugo and two anonymous reviewers for their helpful comments on an earlier draft of this paper. This work was conducted in cooperation with the University of Puerto Rico and supported in part by a grants from the World Bank to the International Institute of Tropical Forestry (Research Support Budget Grant RPO 680-05: 'The catalytic effect of tree plantings on the rehabilitation of native forest biodiversity on degraded tropical lands') through a cooperative research agreement between IITF and The Fundação de Estudos e Pesquisas Agrícolas e Florestais (FEPAF, UNESP-FCA) IITF-96-ICA-003. Additional student scholarship support to C.G.G. Croce, J.C.R. Ferreira was provided by the Conselho Nacional de Pesquisas Cientificas e Tecnológicas (CNPq).

References

Applegate, G.B., Robson, K.J., Kent, G.A., 1993. Afforestation for rehabilitation of degraded land in the tropics. In: Thwaites, R.N., Schaumberg, B.J. (Eds.), Australian Forestry and the Global Environment. The Institute of Foresters of Australia, Canberra, pp. 146–153.

Barbosa, J.M., Barbosa, L.M., 1992. Recuperação de áreas degradadas de Mata Ciliar a partir de sementes. Revista do Instituto Florestal (São Paulo) 4, 702–705.

Brown, S., Lugo, A.E., 1994. Rehabilitation of tropical lands: a key for sustaining development. Rest. Ecol. 2, 97–111.

Bryant, D., Nielsen, D., Tangley, L., 1997. The Last Frontier Forests: Ecosystems and Economies on the Edge. World Resources Institute, Washington DC, 42 pp.

Cámara de Gusmão, I., 1991. Plan de ação para a mata Atlântica. Fundação SOS Mata Atlântica, São Paulo, 152 pp.

de Camargo, D.A., Moniz, A.C., Jorge, J.A., Valadares, J.M.A.S., 1986. Métodos de análise química, minerológica e física de solos. Instituto Agrônomico de Campinas, Campinas, Brazil, 94 pp.

Evans, J., 1982. Plantation Forestry in the Tropics. Clarendon Press, Oxford, 472 pp.

Fernandes, T.S.D., Folster, H., Fassbender, W., Vielhauer, K., Voss, K., Bianchi, H., 1998. Recuperation of degraded pasture using Acacia mangium to return to traditional shifting cultivation system in northeast of Pará, Brazil. In: Proceedings of the third SHIFT Workshop, held in Manaus, Brazil, 15–19 March 1998. Bundesministerium für Bildung und Forschung, Germany, pp. 119–124.

Francis, J.K., 1993. Leucaena leucocephala established by direct seeding in prepared seed spots under difficult conditions. Nitrogen Fixing Tree Res. Rep. 11, 91–93.

Fundação SOS Mata Atlântica, 1992. Dossiê mata atlântica. Fundação SOS Mata Atlântica, São Paulo, 119 pp.

Fundação SOS Mata Atlântica and Instituto Nacional de Pesquisas Espaciais (INPE), 1993. Atlas da evolução dos remnascentes florestais e ecossistemas associados do domínio da Mata Atlântica no período de 1985 a 1990. São Paulo, 22 pp.

Kageyama, P., Santarelli, E., Gandara, F.B., Gonçalves, J.C., Simionato, J.L., Antiqueira, L.R., Geres, W.L., 1994. Revegetação de áreas degradadas: modelos de consorciação com alta diversidade. In: Anais do 1° Simpósio Sul-Americano & 2° Simpósio Nacional de Recuperação de Áreas Degradadas held at Foz do Iguaçu. Fundação de Pesquisas Florestais do Paraná, Curitiba, Brazil, pp. 569–576.

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

Kuusipalo, J., Ådjers, G., Jafarsidik, Y., Antii, O., Tuomela, K., Vuokko, R., 1995. Restoration of natural vegetation in degraded *Imperata cylindrica* grassland: understory development in forest plantations. J. Veg. Sci. 6, 205–210.

Lamb, D., 1998. Large-scale ecological restoration of degraded tropical forest lands: the potential role of timber plantations. Rest. Ecol. 6, 271–279.

Lamb, D., Tomlinson, M., 1994. Forest rehabilitation in the Asia-Pacific region: past lessons and present uncertainties. J. Trop. For. Sci., 157–170.

Lamb, D., Parrotta, J.A., Keenan, R., Tucker, N.I.J., 1997. Rejoining habitat remnants: restoration of degraded tropical landscapes. In: Laurence, W.F., Bierregaard Jr., R.O. (Eds.), Tropical Forest Remnants: Ecology, Management and Conservation of Fragmented Communities. University of Chicago Press, Chicago, IL, pp. 366–385.

Laurie, M.V., 1974. Tree planting practices in African savanas. Forestry Development Paper No. 19, FAO.

Lorenzi, H., 1992. Árvores brasileiras: manual de indentificação e cultivo de plantas arbóreas nativas do Brasil. Nova Odessa, SP: editora Plantarum, 352 pp.

Lübbe, W.A., Geldenhuys, C.J., 1991. Regeneration patterns in planted and natural forest stands near Knysa, Southern Cape. S. Afr. J. For. 159, 43–50.

Lugo, A.E., 1992. Tree plantations for rehabilitating damaged lands in the tropics. In: Wali, M.K. (Ed.), Environmental Rehabilitation, Vol. 2. SPB Academic Publishing, The Hague, pp. 247–255.

Lugo, A.E., Parrotta, J.A., Brown, S., 1993. Loss of species caused by tropical deforestation and their recovery through management. Ambio. 22, 106–109.

Maschio, L.M. de A., Balensiefer, M., Rachwal, M.F.G., Curcio, G., Montoya, L.J., 1992. Evolução, estágio e caracterização de pesquisa em recuperação de áreas degradadas no Brasil. In: Anais do 1° Simpósio Nacional de Recuperação de Áreas Degradadas, held at Curitiba, Universidade Federal do Paraná/ Fundação de Pesquisas Florestais do Paraná, Curitiba, Brazil, pp. 17–33.

Mead, R., Curnow, R.N., 1983. Statistical Methods in Agricultural and Experimental Biology. Chapman and Hall, New York. 335 pp.

Mitra, S.S., Sheldon, F.H., 1993. Use of exotic tree plantations by Bornean lowland forest birds. Auk 110, 529–540.

Parrotta, J.A., 1992. The role of plantation forests in rehabilitating degraded ecosystems. Agric. Ecosyst. Environ. 41, 115–133.

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, Dordrecht, pp. 63–73.

Parrotta, J.A., 1995. The influence of overstory composition on understory colonization by native species in plantations on a degraded tropical site. J. Veg. Sci. 6, 627–636.

Parrotta, J.A., 1999. Productivity, nutrient cycling, and succession in single- and mixed-species plantations of *Casuarina equisetifolia*, *Eucalyptus robusta*, and *Leucaena leucocephala* in Puerto Rico. For. Ecol. Manage. 124, 45–77.

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

Parrotta, J.A., Turnbull, J.T. (Eds.), 1997. Catalyzing native forest regeneration on degraded tropical lands. For. Ecol. Manage. 99, 1–290.

Raij, B., van Quaggio, J.A., 1983. Métodos de análise de solo para fins de fertilidade. Boletim Técnico 81. Instituto Agrônomico, Secretaria de Agricultura e Abastecimento, Campinas, Brazil, 31 pp.

Soni, P., Vasistha, H.B., Kumar, O., 1989. Biological diversity in surface mined areas after reclamation. Ind. For. 115, 475–482.

Sun, D., Dickinson, G.R., 1995. Direct seeding for rehabilitation of degraded lands in north-east Queensland. Aust. J. Soil Water Cons. 8, 14–17.

Sun, D., Dickinson, G.R., 1996. The competition effect of *Brachiaria decumbens* on the early growth of direct-seeded trees of *Alphitonia petriei* in tropical north Australia. Biotropica 28, 272–276.

Sun, D., Dickinson, G.R., Bragg, A.L., 1995. Direct seeding of *Alphitonia petriei* (Rhamnaceae) for gully revegetation on tropical northern Australia. For. Ecol. Manage. 73, 249–257.

Thomson, D., 1992. An efficient broad acre tree establishment technique. Landscape Aust. 4, 313–319.