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Early growth of native and exotic trees planted on degraded tropical pasture

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Abstract

Our goal was to assess the potential of two exotic and five native tree species in reestablishing trees to degraded land in the humid tropics of southern Costa Rica. Our study site was deforested in the 1950s. Steep topography and high rainfall led subsequently to severe erosion, which exposed nutrient-poor, acid, unproductive subsoil. Our site is typical of many tropical overgrazed pastures that have been established in high rainfall areas on ultisols worldwide. Restoration of useful trees to such lands is difficult when erosion is severe.

We established 30 experimental blocks in 1994 across our study site that varied in topography and degree of erosion. We analyzed survival over 7 years and height after 3 and 7 years. *Pinus tecunumanii*, non-native to Costa Rica but native to Central America, was the outstanding performer with best growth and survival among all blocks. Several of the Costa Rican natives, all considered valuable for timber, survived and grew moderately well (*Vochysia guatemalensis*, *Terminalia amazonia*, *Calophyllum brasiliense*).

We assessed the effect of erosion on survival and growth. Survival and/or growth negatively correlated with degree of erosion in five of the seven species. *P. tecunumanii*, an ectomycorrhizal species, survived and grew uniformly well and independently of erosion. *T. amazonia*survived better but grew worse on more eroded sites.

These results suggest the following recommendations for projects that attempt to restore trees to tropical degraded cattle pastures similar to our site:

- areas that have suffered less extreme erosion could be planted successfully with three of the native species studied here: *V. guatemalensis*, *T. amazonia*, or *C. brasiliense*, perhaps in mixtures;
- *P. tecunumanii* is suitable for planting on the most deeply eroded, bare areas and therefore might ameliorate hostile micro sites more quickly than other species;
- our results suggest that the pine should be tested as a site-preparing species by intermixing seedlings of more shade loving species two or more years after planting the pine;
- a system of crop rotation might be sustainable, planting pine as a rapidly growing frequently harvested species and interplanting more slowly growing but more valuable species.

Keywords: *Terminalia amazonia*; *Vochysia guatemalensis*; *Calophyllum brasiliense*; *Pinus tecunumanii*; *Tabebuia ochracea*; *Cedrela odorata*; *Eucalyptus deglupta*; Degraded pasture; Tropical reforestation; Tree plantations; Costa Rica; Tropical restoration

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1. Introduction

Large areas of deforested and degraded land exist in the humid tropics (NASA, 2003). In the decade of the 1990s approximately 0.38% per year of the worlds forests were converted to other land uses. Some land reverts to forest, but the net annual loss of forest approaches 0.22% (FAO, 2001). The annual rate is much higher in many developing countries, where some 200 million ha of forest are estimated to have been lost in the period 1980–1995 (FAO, 1997). About 350 million ha of previous forest are unlikely to regenerate spontaneously, including 155 million ha in the Americas (ITTO, 2002). Common soil problems in the deforested tropics include aluminum toxicity, low pH and phosphorous fixation (Fisher, 1995). Many such areas are difficult to reforest even with current methods of intervention. In our project, we hope to provide information for developing methods of rehabilitating land that is on the verge of abandonment.

At a given site in the humid tropics, either ‘‘exotic’’ or native tree species may perform better. Among the commonly planted exotics are various tropical pines, *Eucalyptus* spp., *Tectona grandis*, *Gmelina arborea* and some *Acacia* species. Annandale and Keenan (1999) studied a range of species in tropical northern Queensland, Australia. They tested *Eucalyptus pellita*, *E.grandis* × *E. tereticornis*, *T. grandis*, *Acacia mangium*, and several provenances of *Cedrela odorata*, as well as *Pinus caribea* var. *hondurensis*. On their degraded lowland tropical site, the pine achieved by far the best growth after 10 years.

Interest in establishing plantations of native species has grown in recent years (Gonzalez and Fisher, 1994; Montagnini, 2000; Piotto et al., 2002). Although, some native species (e.g. members of Meliaceae) may be less broadly adapted and more susceptible to native pests, others may be well suited to particular conditions such as low levels of soil nutrients characteristic of degraded land (Nichols et al., 1997).

Our general aim was to find species with potential to rehabilitate tropical sites similar to our degraded pasture in southern Costa Rica. Our specific objectives were to

- evaluate the performance of seven tree species planted on degraded land;
- evaluate the impact of land erosion on seedling growth and survival of each species;
- recommend potential combinations of methods to better rehabilitate such sites.

2. Materials and methods

2.1. Study site

The study site is a 25 ha farm in southwestern Costa Rica, 20 km south of the town of San Vito de Coto Brus, 83°W longitude, 9°N latitude. Elevation is 1050 m on the south Pacific slope, where the terrain frequently intercepts heavy fog. Mean annual temperature is 20 °C. Annual precipitation averages 4400 mm, most falling between April and December with peaks in May and October. In the Holdridge system of life zones (Holdridge, 1967) the site was ‘‘humid premontane tropical rainforest’’ before clear cutting for coffee in the 1950s. This region of Coto Brus is characterized by steep rugged terrain not appropriate for crops or pasture because of thin topsoil and vulnerability to erosion (Laurent, 1992). Nevertheless, the area has been settled and intensively cropped for half a century.

In 1976, the area was partly converted from coffee to different uses. Some areas of the study site were kept in coffee for 10–20 more years. Most of the rest was converted to cattle pasture about 1978 by planting grass species *Paspalum micay*, *Brachiaria* sp and *Melinus minutifolia* (Poaceae).

In the 1970s, the pasture produced twice as much beef as it did by 1990. By 1990, the land showed serious signs of overgrazing, with barren, deeply incised cattle trails occupying about 50% of the land surface area. The three most deeply eroded areas on the farm had cattle trails up to 2 m deep. The largest of the areas was completely bare, lacking even grass roots.

Soils on the farm are acid, phosphorous-fixing and infertile—more so after erosion removes topsoil (Carpenter et al., 2001). The soils are influenced by the presence of a major volcano (Volcan Baru) 40 km to the east in Panama and others farther north in Costa Rica. The current USDA system classifies the soils as ultisols, from typic hapludults to humic or andic hapludults. The range of clay is 17–26%, silt

Table 1
Scientific names, common names, origin, wood density of seven tropical tree species

Scientific name	Family	Origin	Density of wood (g/cm^3)	Planting size	No. seed mothers
Natives					
T. ochracea (Cham.) Standl.	Bignoniaceae	Honduras–Brazil	0.85	6 cm seedling	2
C. brasiliense (Camb.)	Clusiaceae	Neotropics	0.72	33 cm seedling	8
C. odorata L.	Meliaceae		0.59	21 cm seedling	7
T. amazonia (Gmel.) Excell	Combretaceae	Mexico–Brazil	0.61	39 cm seedling	3
V. guatemalensis Donn. Smith	Vochysiaceae	Central America	0.37	30 cm seedling	10
Exotics					
E. deglupta Blume	Myrtaceae	New Guinea	0.49	54 cm seedling	Unknown
P. tecunumanii (Schw.) Equiluz et Perry	Pinaceae	Mexico–Central America	0.53	48 cm seedling	Unknown

19–28% and sand and sand-sized particles 48–64%. Physical structure is good—even at the bottom of the cattle trails values for bulk density do not exceed 1.

2.2. *Tree species*

We selected seven species for assay (Table 1), including two non-native species, *E. deglupta*and *P. tecunumanii*. These two species were included in local reforestation projects by Costa Rican foresters at the time our study began in 1994. *P. tecunumanii* is among the best known of the neotropical pines and considerable research on its genetic improvement has been done (Hodge and Dvorak, 1999; Dvorak et al., 2000, 2001).

Among the five native species were two ‘‘climax’’ hardwood species expected to grow relatively slowly, *Calophyllum brasiliense* (family clusiaceae) and *Tabebuia ochracea* (Bignoniaceae). The other three are ‘‘long-lived pioneers’’: *Vochysia guatemalensis* (Vochysiaceae), an early successional species with low density but usable timber; *Cedrela odorata* (Meliaceae), well-known as a high-value timber; and *Terminalia amazonia* (Combretaceae), which produces attractive wood used for many purposes.

Recent years have seen several studies of *Vocyhsia* species both in natural forest (Herrera et al., 1999; Vera et al., 1999; Herrera and Alvarado, 2001) and in plantations (Gonzalez and Fisher, 1994; Montagnini, 2000; Carnevale and Montagnini, 2002; Moulaert et al., 2002). There have been increasing attempts to understand and develop the genetic potential of species in the genus (Cornelius and Mesen, 1997; Gonzalez and Fisher, 1998,1997; Mesen and Cornelius, 2000). Other studies have identified *Vochysia* spp. as species that can tolerate strongly acid soils, accumulate Al and grow well in soils with moderately high exchangeable Al and low exchangeable base cations (Perez et al., 1993).

T. amazonia is also known as *T. amazonica*, although, the former spelling is preferred (CABI database 1995–2003). Earlier generations of foresters developed the silviculture of *T. amazonia* (Marshall, 1939). Its use as a plantation species has increased in recent years in humid areas of Costa Rica (Nichols and Gonzalez, 1992; Gonzalez and Fisher, 1994; Nichols, 1994; Nichols et al., 1997, 2001; CAB International, 2000; Montagnini, 2000; Piotto et al., 2001; Torres and Lujan, 2002; Ugalde et al., 2002; Fonseca and Chinchilla, 2002). This species ranges widely from Mexico through the Caribbean and Central America to Brazil and occurs on a wide variety of soils. Its moderately dense wood is yellow, often with reddish streaks and is highly versatile, being used for general-purpose construction and furniture.

2.3. *Nursery procedures*

We attempted to obtain seeds from several mother trees in case seed viability and seedling performance varied between provenances. Between 1993 and 1994 we located variable numbers of mother trees of four of the five natives (Table 1) in local forests and farms and collected seeds directly from their canopies by using climbing gear. These seeds were sown in germination beds and transplanted into black plastic nursery bags. We inoculated each nursery bag with mycorrhizal fungi by inserting about 10 cm^3 of soil gathered from under the mother trees into the top layer of potting soil. We fertilized the seedlings about 2 weeks after transplantation to the nursery bags. A local nursery managed by the organization for tropical studies provided seedlings from eight mother trees of *C. brasiliense* located in our region.

We also used material from local nurseries for the two exotic species. We obtained seeds for *E. deglupta* from the local high schools forestry project. Another local nursery provided seedlings of *P. tecunumanii*. These had been inoculated with soil from a healthy plantation of this pine species to provide the appropriate mycorrhizal fungi. In the cases of *E. deglupta* and *P. tecunumanii* the number of mother trees was therefore unknown (Table 1).

Seedling size varied among species but in general did not reflect time in the nursery. For example, seedlings of *T. ochracea* were small when out planted (Table 1) but spent more time in the nursery than any other species.

2.4. Experimental design

In July–August 1994, we established 30 experimental blocks to capture the various terrains and degrees of erosion across the farm (Fig. 1). Terrain is extremely heterogeneous changing over short distances from flat ridge tops, to steep (20–45°) slopes to flat areas at the foot of slopes to gentle valleys or rolling hills. Terrain and degree of erosion were homogeneous within each block. All blocks occupied overgrazed cattle pasture.

All seedlings were planted 3 m apart (Fig. 2). Location of the plot for each species within the array was determined randomly for every block. Each species was represented by one plot per block and three individuals per plot (different seed mothers where possible) for a total of 90 trees per species in the experiment.

2.5. Measurements and analysis

We measured seedling height after out planting in 1994 and annually through 2001, noting seedling deaths. Once trees were over 122 cm tall, we measured dbh. For each species we calculated 7 years survival, means of height and diameter for each plot and volume according to the index $(0.298 \times (\text{dbh}/100)^2(\text{height}/100))$ (Hayward, 1987).

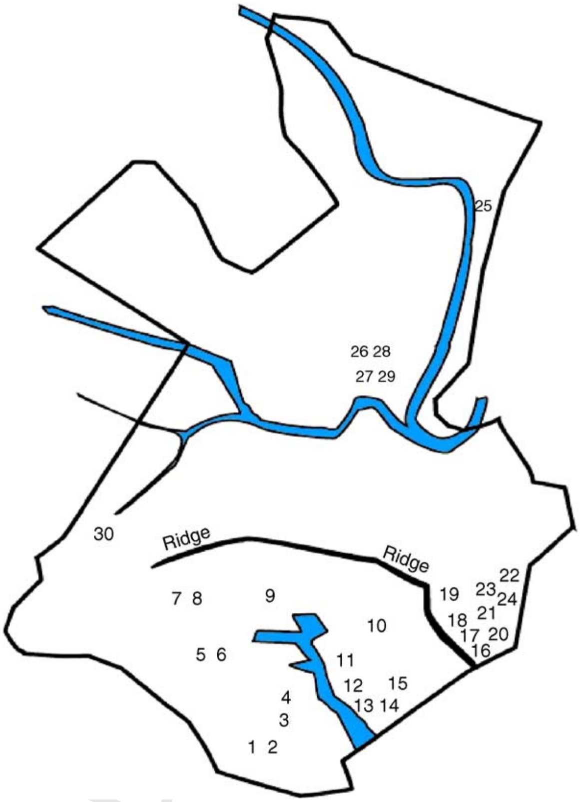

Fig. 1. Map of the 25 ha farm with 30 experimental blocks indicated. Placement of the blocks captured different degrees of erosion and terrains across the farm.

We estimated the degree of erosion in each block in August 1997, using depth and expanse of cattle trails to assign an index from 1 to 10. These signs of erosion do not change on this degraded farm for years because natural succession proceeds slowly. First, we observed the range of erosion in the 30 blocks by locating the least and most eroded blocks. We chose 1 as the index

```
V  V  V  A  A  A
  O  O  O  B  B  B
P  P  P  T  T  T
  E  E  E  x  x  x
```

Fig. 2. Planting pattern within a single block. Different letters indicate different species, three seedlings per species. The plots for each species were assigned at random in each block. X indicates a plot with no seedlings planted for this experiment; these plots also were assigned locations randomly.

for the one block that showed the least erosion. Although, no topsoil remained in this block, it contained a well-formed B horizon and only shallow cattle trails. In contrast, an index of 10 represented the most eroded blocks of the 30. These blocks were eroded to the parent material and some contained cattle trails 2 m deep. The values 5–6 represented average erosion between these extremes. Each of four observers scored the blocks independently from 1 to 10. The four values were consistent for a majority of the blocks. We later averaged the four values from each block to obtain the index of erosion for that block.

We applied the univariate general linear model in SPSS to test differences in growth rates between species and post hoc Tukeys ($\alpha = 0.05$) to differentiate groups. We used Pearson's rank correlation to determine the relationship between erosion and performance. We did not apply statistics to survival rates because the treatments (species) were replicated only three times within a block.

3. Results

3.1. Species survival after 7 years

By 2001 average survival differed greatly among species (Fig. 3). Highest mortality occurred in *T. ochracea* and *E. deglupta*. At the other extreme were survival rates of about 90% in *P. tecunumanii* and *V. guatemalensis*. Approximately half the seedlings survived of *C. odorata* and *C. brasiliense*.

3.2. Growth at 3 and 7 years

We analyzed growth in the top five surviving species, eliminating from consideration *T. ochracea* and *E. deglupta*. Heights after 7 years of growth differed significantly among species (Table 2).

Plotting heights in increments (Fig. 4) suggest that growth may be slowing in both *T. amazonia* and *C. odorata*. In contrast, growth rates appear to be stable in *C. brasiliense*, and to be accelerating in *V. guatemalensis* and *P. tecunumanii*. Although, the pine and *V. guatemalensis* had similarly high rates of survival, *P. tecunumanii* had superior growth, achieving a mean height of over 10 m in 7 years. This growth rate significantly exceeded that of all other species and is accentuated when shown as calculated volumes at the end of 7 years of growth (Fig. 5).

3.3. Relationship of survival and growth to erosion

The tree species differed in how survival related to erosion (Table 3). For *E. deglupta* and *C. odorata* the correlation was significantly negative, with higher mortality on more eroded sites. For *T. amazonia* the correlation was significantly positive, with higher mortality on less eroded sites. Mortality did not correlate significantly with erosion for the remaining species.

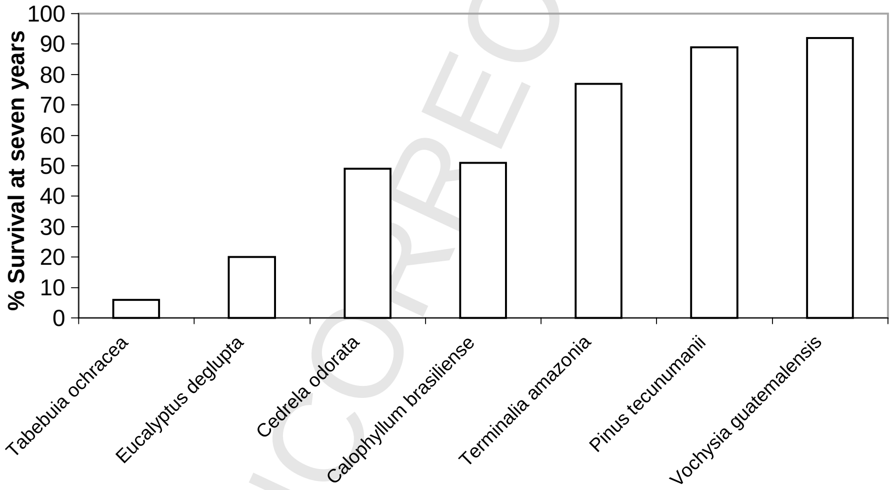

Fig. 3. Percent survival after 7 years in the field, based on the initial 90 individuals planted per species.

Table 2
One-way ANOVA with species as the factor

Source	Type III sum of squares	d.f.	Mean square	*F*	Significance
(A) Variable is tree height at 7 years					
Species	31246562	4	7811640	156.3	0.000
Error	15795539	316	49986		
Species		*n*	Mean	S.E.	
(B) Variability (S.E.) in tree height (cm) at 7 years					
C. odorata		44	224.3	32.9	
P. tecunumanii		79	1054.6	30.4	
T. amazonia		69	302.3	26.9	
V. guatemalensis		83	421.4	23.7	
C. brasiliense		46	386.1	20	

Adjusted R^2 is 0.660.

Growth negatively correlated with our index of erosion in all species except *P. tecunumanii* (Table 3). Fig. 6 shows the variability in erosion and overall tree mortality and growth across all 30 blocks. Tree performance was exceptional in Block 21, where the erosion index was third-lowest of the 30 blocks and the terrain is a shallow valley.

4. Discussion

4.1. Relative performance of species for reforestation projects

Clearly, we would not recommend using species or methods with poor survival. We recommend against using *T. ochracea* or *E. deglupta* in deeply eroded ultisols. *T. ochracea* may be better adapted to shaded conditions on the forest floor than to open pasture. Although, seedlings grew in the nursery for 6–7 months, they remained small in above-ground stature by out planting time. Small size may have been a factor in their poor survival.

E. deglupta naturally occurs on tropical alluvial flats with fertile well-drained soils (Eldridge et al., 1994). We doubt that typically degraded soils will support good growth of this species. In fact, local foresters now recommend against planting this species in degraded areas of Coto Brus.

In contrast, the pine and most of the other four natives have potential for reforestation of degraded land.

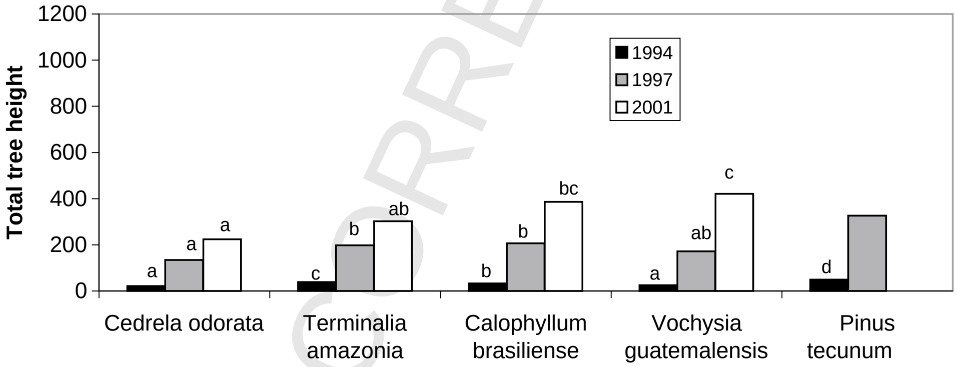

Fig. 4. Tree heights at three points in time: at initial out planting in 1994, after 3 years of growth and after 7 years of growth. Data for the five best-surviving species are shown. Letters indicate significant differences between species within a year, $\alpha = 0.05$.

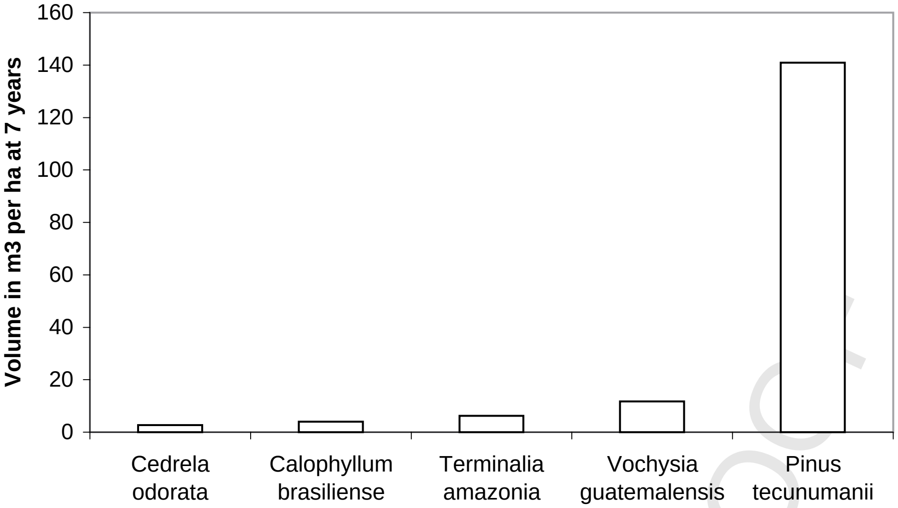

Fig. 5. Volumes in m^3 per ha for each species after 7 years of growth, calculated as $[0.298 \times (\mathrm{dbh}/100)^2(\mathrm{height}/100)]$. The superior volume of pine was partly a function of large diameters.

4.2. Reforesting eroded tropical land: goals and recommendations

Reforestation projects on degraded sites may have different objectives, among them to:

1. reduce erosion;
2. reestablish a variety of native species;
3. establish economically viable commercial plantations;
4. combine two or more of the above goals.

First, land that is severely eroded and bare, with no roots, continues to erode. Erosion control involves protecting the soil with vegetation cover and root systems. If a projects reforestation goal is to reduce erosion as quickly as possible on extremely degraded sites, *P. tecunumanii* likely would be the best candidate among the seven species we tested. This species alone grew in parent material where not even grasses succeeded over the 7 years period of the project. Its survival and growth were even independent of the magnitude of the erosion.

If the goal, however, is to reestablish a variety of natives, the soil cannot be too degraded. None of the natives assayed here grew when planted on soil eroded to the C horizon. In areas with remnant B horizon, our results suggest that a combination of *V. guatemalensis*, *T. amazonia*, *C. brasiliense* and even *C. odorata* would work.

Table 3
Correlations of 7 years survival and tree height with erosion index

Species	Survival		Height	
	r	One-tailed (*p*)	*r*	One-tailed (*p*)
E. deglupta	−0.66	<0.001	n/a	
C. odorata	−0.45	0.006	−0.57	<0.001
T. amazonia	0.33	0.04	−0.42	0.01
T. ochracea	−0.25	0.09	n/a	
P. tecunumanii	−0.23	0.11	0.05	0.25
V. guatemalensis	−0.16	0.2	−0.74	<0.01
C. brasiliense	−0.12	0.26	−0.44	0.015

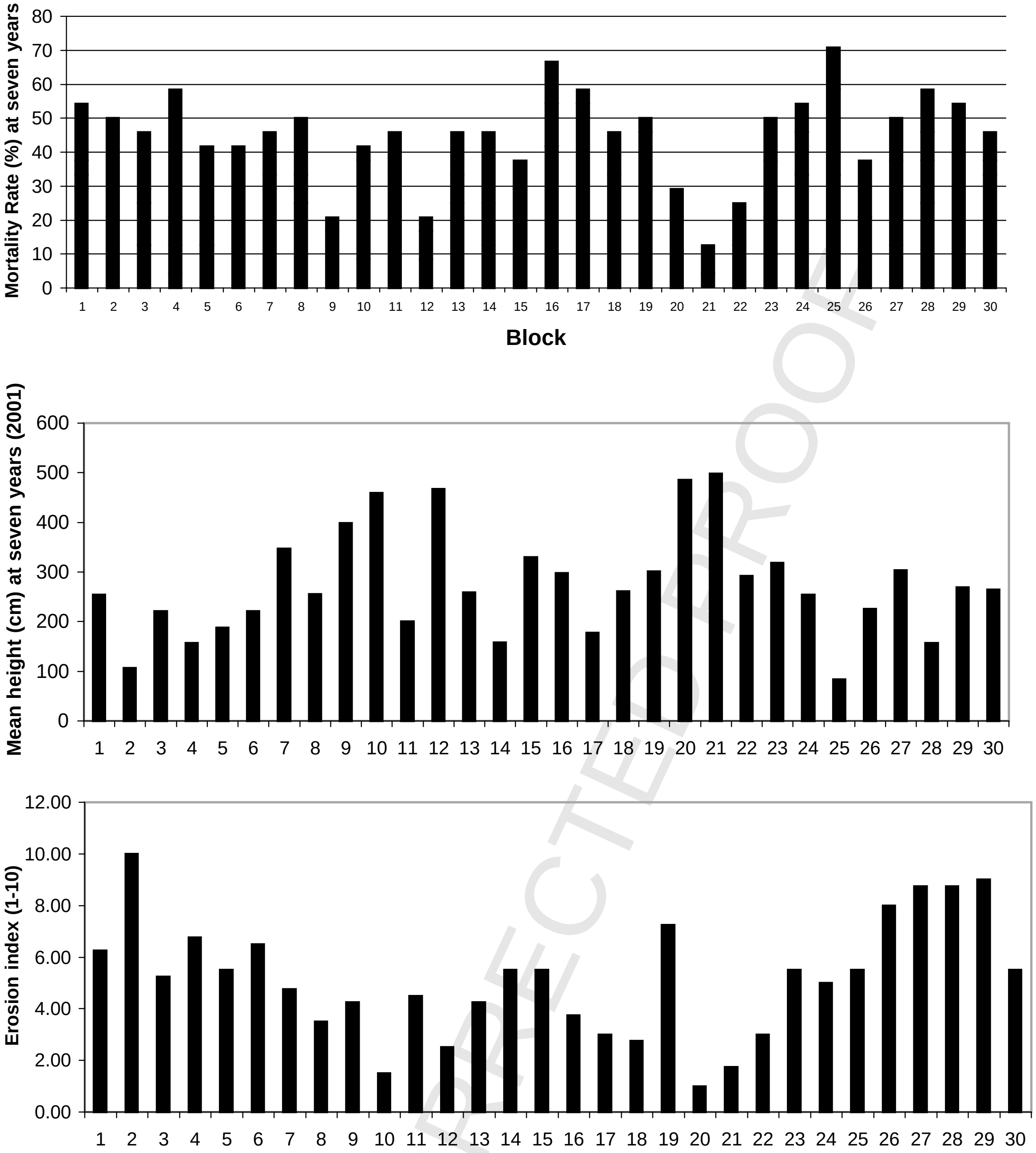

Fig. 6. Means of three variables indicated for all 30 plots—top: mortality rate at 7 years after out planting, for all tree species; middle: mean height after 7 years of growth, averaged across all species; bottom: average.

Planting pine initially might prepare a badly degraded area for later planting or regeneration of native species. A method of intermixing seedlings of shade loving species 2 or more years after planting the pine might be more successful than planting such native species directly onto degraded sites. Relative to bare eroded pasture, microclimates under any trees, including pine, are less severe. Pine might also suppress competition from weeds and grasses by shading the surface. Lugo (1997) discusses this use of exotic plantations in the introduction to a journal issue (Forest Ecology and Management, No. 99, 1997) dedicated to the topic of facilitating natural forest establishment through plantations, in which examples from around the world are provided. Articles specifically documenting the use of pines to regenerate native forest include (Geldenhuys, 1997; Keenan et al., 1997; Loumeto and Huttel, 1997; Oberhauser, 1997). In our project *P. tecunumanii* established well enough in less than 3 years to provide perches for seed dispersing bats and birds.

The third goal above is more directly economic. If the goal is to produce a commercial plantation with a fast rotation time, pine was the only viable species of the seven, especially on the most degraded sites. However, some landowners prefer to use native tree species in plantations. Among the natives *V. guatemalensis* showed the best survival and growth. *Vochysia* species (*V. guatemalensis* and *V. ferruginea*) are common as seedlings in many early successional forests in much of the lowland areas of neotropical rainforest.

However, the cut timber of *Vochysia* spp. and the trunks of live trees are apparently quite susceptible to termite attack (Nichols and Gonzalez; 1992; Gallatin, personal communication). Therefore, rotations for timber production should probably be short (10–20 years). Perhaps these species are best employed like pine to capture sites by growing quickly, reducing erosion and shading out grasses and other weeds.

C. brasiliense is a widespread native neotropical species that is attractive and has moderately valuable wood. Although, it survived well and grew moderately in our study, in another nearby area (Loik and Holl, 1999) it appeared to tolerate full sunlight poorly. A review of the silvicultural literature (CAB International, 2000) found that this species is generally considered to be better adapted to partial shade than to open conditions. Some studies suggest that this is not unusual: many later successional stage trees grow better in partial shade (6–42% of full irradiance) than in full sun (Agyeman et al., 1999). One possible forestry strategy might be to moderate a badly degraded site with pine or *Vochysia* before planting *C. brasiliense*. The faster growing species could provide a harvest on a short rotation cycle, while *C. brasiliense* could serve as a long-term investment for the landowner.

4.3. Possible role of mycorrhizal fungi in tree performance

Why was the pine more successful than any of the other species, most of which were native and presumably adapted to local conditions? First, a pasture where the original forest was removed over 50 years ago is obviously different from the understory of native rainforest. Our species adaptations may no longer be relevant.

Second, pines perhaps did best because they are ectomycorrhizal. Pine seedlings do not survive if not inoculated, and nursery technicians usually inoculate them appropriately. Therefore, we can assume that the appropriate fungi had colonized our pine seedlings before out planting. Most native neotropical species are endomycorrhizal (Janos, 1996), having relationships with arbuscular mycorrhizal fungi (hereafter, ‘‘AMF’’). Conceivably our techniques for inoculating the native tree species with AMF were less adequate. AMF improve phosphorous nutrition in their host plants when growing in P-deficient soils (O’Neil et al., 1991; Cooperband et al., 1994).

Finally, the native tree species with the poorest growth in our site may need specific types of AMF. Shepherd et al. (2003) did find AMF in our slowest growing natives, *T. ochracea* and *C. odorata*. However, to date, identification of fungi has been done at the generic level. On going analysis will show whether different tree species contain different fungal species. Such information in the future might help explain the poor performance of some natives and offer clues about how to use AMF to aid reforestation in the tropics.

4.4. Effect of erosion on performance

The correlation analyses based on our erosion index could not determine causation. However, they did suggest that erosion had a strong negative impact on both survival and growth of most species. Erosion not only reduces the mineral fertility of the soil, but also changes its physical structure and biological community. Carpenter et al. (2001) showed that the number and diversity of AMF spores are low on the most eroded sites on this farm. Scarcity of natural inoculum could account for poor performance on the deeply eroded sites. At our site Andonian (2001) experimentally inoculated AMF spores into nursery bags with germinating seedlings. Inoculation improved performance in five of six species. DNA analysis of fungi in root samples was consistent with the nursery results (Shepherd et al., 2003). Eleven of 12 species were colonized by AMF, including four of the five native species of the present report.

T. amazonia was the odd species in both the nursery experiment and the DNA analysis, neither responding to inoculation (Andonian, 2001) nor containing AMF in the field. Interestingly, *T. amazonia* also was the only species for which survival increased with increasing erosion. This species grows well despite low levels of soil phosphorous (Nichols et al., 1997) even though it is not mycorrhizal. In contrast, grass and weeds do not grow well in extremely eroded areas on this study site. Perhaps *T. amazonia* survived better the worse the erosion because of less competition from other vegetation. Also, all other native species in the study are endomycorrhizal and would suffer from lack of AMF in deeply eroded areas. So, besides the benefit of lower competition, *T. amazonia* would not have suffered inhibition due to lack of AMF. Nevertheless, growth of this species declined with erosion, so overall performance was poor despite better survival in deeply eroded blocks.

5. Conclusions

For rehabilitation of extremely eroded pasture sites similar to the one in this study, *P. tecunumanii* could establish vegetative cover relatively quickly. This species also might produce usable timber rapidly, but more time is necessary to establish the economics of this pine. Foresters should consider *V. guatemalensis* and possibly *T. amazonia* and *C. brasiliense* if native species are desired.

We saw a clear relationship between our erosion index and tree performance of most species. Only pine performed independently of the degree of erosion. The negative impact of erosion may relate to effects on soil biota, a possibility that we are currently investigating. Methods that reduce erosion are probably important for establishment of tree seedlings.

Finally, future work should test the ability of pine to prepare a site for later planting of other species. Studies should pursue the possibility that restoring soil AMF communities could facilitate tree restoration in severely eroded areas. This paper reports a long-term experiment, which we plan to continue measuring in the future, as rankings could change among the species over time.

Uncited references

Davidson et al. (1998), Hofer (2002), Marques and Joly (2000), Prokopy (2001), Sullivan et al. (1998).

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