Methods of facilitating reforestation of tropical degraded land with the native timber tree, *Terminalia amazonia*

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Abstract

We experimentally compared the effect of fertilization to the effect of interplanting two species of legume trees (*Inga edulis* and *Glinicidia sepium*) on growth of a native tropical tree, *Terminalia amazonia* (Combretaceae). The experiment was a randomized block design with trees planted in eroded cattle pasture in Southern Costa Rica. After 8 years, both block and treatment significantly explained variance in tree growth. Blocks differed in degree of erosion and initial soil nitrate and phosphate. All three factors significantly predicted tree growth, erosion negatively and N and P positively. However, erosion best explained block effect. Fertilizer (10N:30P:10K) had no effect on tree growth. In the treatments with legume trees, *I. edulis* survived and grew better than *G. sepium*. Concordantly, plots in which *I. edulis* was interplanted with *T. amazonia* showed a stronger positive effect on *T. amazonia* than plots in which *G. sepium* was the interplanted species. Possibly *I. edulis* increased nitrogen availability and-or aided growth by partial shading. A treatment that mixed all three species also improved growth of *T. amazonia* significantly over controls. This result suggests that fertilizing native trees outplanted for restoration or forestry may be wasted investment. However, intermixing legume trees may increase economic benefits to farmers interested in reforesting degraded land.

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1. Introduction

1.1. Background

Deforestation represents one of the planet’s most significant environmental and economic problems (FAO, 2001; NASA, 2003). The crisis is particularly severe in wet tropical regions where soil fertility is generally poor (Aber and Melillo, 1991) and erosion is severe (Lal, 1986; Carpenter et al., 2001; Khamsouk and Roose, 2003; Angima et al., 2003). As land use increases with growing human populations, deforestation and its negative effects are likely to worsen (Chazdon, 2003). Reforesting at least parts of degrading farms should help to reduce erosion and restore soil fertility. This paper presents 8-year results...
of an experiment in Southern Costa Rica (Nichols et al., 2001) that seeks ways to reforest such land economically.

The classic paradigm for forest loss in the Neotropics involves clearing forest for agriculture. A combination of factors lead to erosion and reduction in soil fertility, abandonment of the degraded land and subsequent clearing of other forested areas for new crop land (Buocuher et al., 1983). In the final stage, abandoned agricultural fields may continue to erode (Zhang et al., 2004) or become dominated by invasive grasses, impeding native forest regeneration (Nepstad et al., 1991; Holl et al., 2000). This cycle may be broken at any stage by intervention to improve sustainability of land use. Methods of intervention that quickly provide economic benefits to farmers are more likely to be adopted than slower methods.

Planting tree species that tolerate degraded conditions is one option for stimulating forest regeneration. Additionally, trees that ameliorate poor soil would be attractive for farmers to plant by providing indirect economic benefits (Diaz-Pena, 1995). Some legumes (family: Fabaceae) improve degraded soils by increasing soil nitrogen (Fenclal et al., 1998). A growing number of studies suggest that woody legumes aid forest regeneration (Tarrant, 1961; MacDicken, 1994; Franco and DeFaria, 1997; Gathumbi et al., 2002), perhaps through their effect on soil nitrogen. Franco and DeFaria (1997) found that legume trees planted on degraded land provide up to 12 tonnes of litter and 190 kg of N ha\(^{-1}\) year\(^{-1}\). Legumes in Sub-Saharan Africa significantly improved soil fertility when interplanted with rotating crops (Buresh and Tain, 1997).

Another economic benefit of legumes is their ability to increase production of a neighboring tree. Planting legumes has been shown to influence growth of intermixed non-leguminous species (MacDicken, 1994). In temperate forest, loblolly pine (\textit{Pinus taeda}) grew faster when interplanted with black locust (\textit{Robinia pseudoacacia}; Groninger et al., 1997). In the tropics, studies show that various species of \textit{Eucalyptus} grow better when mixed with such woody legumes as \textit{Albizia} and \textit{Acacia} (DeBell et al., 1985; Khanna, 1997; Binkley et al., 2003), Balieiro et al., 2002 found that \textit{Eucalyptus} grown with the legume \textit{Pseudosamanea guachapele} grew faster than in monocultures. The effect of herbaceous legumes has also been investigated (Nwonwu and Obiaga, 1988; Nichols et al., 2001; Gathumbi et al., 2002) but has demonstrated less success at improving neighboring tree growth.

Interplanting legumes may also provide farmers with increased diversity of useful products (Gutteridge and Shelton, 1993). Many legume species including \textit{Tamarindus indica}, \textit{Albizia alba} and \textit{Leucaena leucocephala} produce good fuel wood and edible seeds and fruit (Sinha, 1977; www.folklife.si.edu/maroon/foodways/tropical_rainforest_edible_-plant.htm).

We planted an economically valuable native tree in an experiment to compare the impact of fertilization to that of intermixing legume trees on tree growth and health. We also assessed whether initial soil conditions affected growth.

### 1.2. Hypotheses

We established eight experimental treatments to:

1. determine if growth of \textit{Terminalia amazonia} is sufficient on deeply eroded pasture for use in restoration or plantation forestry at our altitudes;
2. test the hypothesis that intermixed legumes positively affect growth of \textit{T. amazonia};
3. test the hypotheses that initial soil N, P and degree of erosion affect subsequent growth of \textit{T. amazonia}.

Our a priori predictions were that unfertilized (control) and fertilized treatments of \textit{T. amazonia} would represent the lower and upper limits, respectively, for growth of this species. These limits would establish the range for comparing growth in mixed legume treatments. We expected that \textit{T. amazonia} mixed with legumes would grow better than controls, assuming the legumes in our experiment would grow well enough to potentially affect the target tree. The prediction followed from previous work showing that both these legume species are nitrogen-fixers and have proven useful in agricultural systems (see below).

Additionally, we predicted that initial soil conditions would affect subsequent tree growth. Specifically, we predicted that higher initial soil nitrogen and phosphates would improve growth, and greater levels of erosion would be associated with decreased growth. The negative effect of erosion is known for
many plants. We based our prediction about nitrogen on the conclusion of Nichols et al. (1997) that this species is apparently nitrogen-limited. We based our prediction about phosphorus on the fact that the soils on this farm are typical Ultisols (Carpenter et al., 2001) with extremely limited amounts of extractable P.

2. Methods

2.1. Site description

The study site is a 25 ha farm on the Pacific slope of Southwestern Costa Rica, 20 km S of San Vito de Coto Brus, 83°W longitude, 9°N latitude. Elevation is 1050 m south-facing slopes often intercept heavy fog in the afternoons. 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 inappropriate for crops or pasture because the thin topsoil erodes easily (Lauren, 1992). Nevertheless, the area has been settled and intensively cropped for half a century.

In 1976, the site was partly converted from coffee to different uses. Most of the area was converted to cattle pasture around 1978 by planting Paspalum micay, Brachiaria sp. and Melinus minutifolia (Poaceae). By 1990, the land showed serious signs of overgrazing. Bare, deeply incised cattle trails occupied about half the surface area. The three most deeply eroded areas on the farm had cattle trails up to 2 m deep. The largest of these areas was completely bare, lacking any roots to hold the soil. Since purchase for research in 1992, the land has suffered five major landslides, three of them within the area of this experiment.

Soils on the farm are acid, phosphorus-fixing and infertile, especially after erosion removes topsoil (Carpenter et al., 2001). The soils range from Typic Hapludults to Humic or Andic Hapludults according to the current USDA system of classification. The range of clay is 17–26%, silt 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 did not exceed 1 in 1993.

2.2. Study species

All plants in this study have alternative uses for local farmers, including fuel wood, fodder, edible fruits, living fence-posts and timber. Our focal timber tree, T. amazonia, is distributed from Southern Mexico to Brazil (Chudnoff, 1984). In Costa Rica it occupies elevations from sea level to 1200 m. We chose T. amazonia both for the quality of its timber and for its adaptability to a variety of tropical soil conditions (Gonzalez and Fisher, 1994; Nichols, 1994; Haggard et al., 1998; Montagnini, 2000; Pietto et al., 2003a,b). Nichols et al. (1997) showed that plantations of T. amazonia survived and grew moderately well even without weed control. The growth of this species may be limited by soil nitrogen (Nichols et al., 1997).

We chose two species of woody legumes to interplant with the focal species, Inga edulis and Gliricidia sepium. I. edulis is native throughout South America (Lawrence et al., 1995) and is commonly used as a shade tree in coffee and cacao plantations. This species has high nitrogenase activity (Tilki and Fisher, 1998) and its leaves decompose relatively slowly due to high levels of phenolics (Palm and Sanchez, 1991). Other commonly planted legumes, such as Erythrina sp., have higher decomposition rates, which may have less long-term benefits. Fisher (1995) demonstrated that soil planted with I. edulis improved in organic C, total N, surface bulk density and extractable P after only 3 years. I. edulis provides fuel wood and an edible fruit (Lawrence et al., 1995).

G. sepium has been recognized by agro-foresters as one of the major N-fixing tree species in the humid tropics (Nair, 1993; Barreto and Fernandez, 2001). Some of its uses include timber, fuel wood, fodder, living-fences, alley cropping and shade for shrub crops such as coffee. Also, Gliricidia leaves contain pest-repellant chemicals (Glover, 1989) that might potentially reduce herbivore loads when mixed with other plant species.

Initially, we included a treatment with several species of herbaceous legumes mixed with T. amazonia. However, none of the herbaceous legumes established, and after 4 years, growth of the focal tree did not differ from controls (Nichols et al., 2001).
2.3. Nursery and planting methods

We collected seeds from 14 mother trees of *T. amazonia* in the vicinity of the study site between late May and late June 1993 (Nichols et al., 2001). Tree seedlings were raised in the nursery on the farm. In September 1993, seedlings approximately 5 cm in height were outplanted. Seedlings that suffered mortality within the first 2 months were replaced. We pruned bifurcating *T. amazonia* according to normal forestry methods.

*I. edulis* seeds were obtained from three nearby mother trees, raised in the nursery and outplanted in July 1993. In some plots, *I. edulis* trees grew more vigorously than *T. amazonia*; in these cases we repeatedly pruned them to prevent light competition. Stake cuttings of *G. sepium* were obtained from healthy trees in the region and laid horizontally for several days until callus formed. Stakes were planted in August 1993; dead stakes were replaced in March 1994.

2.4. Treatments

Table 1 shows the eight different treatments applied in 1993, grouped into three categories: those without interplanted legumes, mixtures containing herbaceous legumes, and mixtures containing woody legumes. The density of *T. amazonia* was constant in all plots at 1111 ha\(^{-1}\). Fig. 1 illustrates a single treatment plot for

![Diagram of experimental plot]

**Fig. 1.** Example of an experimental plot, in this case, treatment 8 (T8). This treatment alternates *I. edulis* and *G. sepium* among the *T. amazonia*. *T. amazonia* are spaced at 3 m.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The eight experimental treatments, T1–T8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No interplantings</strong></td>
<td></td>
</tr>
<tr>
<td>T1 Control</td>
<td><em>T. amazonia</em> seedlings were planted in 1 m diameter clearings; the only manipulation was periodic weeding, concurrent with all other treatment plots</td>
</tr>
<tr>
<td>T2 Fertilized</td>
<td>50 g of 10% N, 30% P, 10% K upon planting in 1993; we re-fertilized in 1994 and in 1995 (Nichols et al., 2001)</td>
</tr>
<tr>
<td><strong>Herbaceous legumes</strong></td>
<td></td>
</tr>
<tr>
<td>T3 Edible beans</td>
<td>Dry beans (<em>P. vulgaris</em>) were sown between the rows of <em>T. amazonia</em> seedlings by frijol tapado (Thurston, 1997)</td>
</tr>
<tr>
<td>T4 Cover crops</td>
<td>A mix of seeds of <em>Mucuna pruriens</em> and <em>Canavalia ensiformis</em> was sown between each pair of adjacent <em>T. amazonia</em> seedlings during the rainy seasons in 1993, 1994 and 1995</td>
</tr>
<tr>
<td><strong>Legume trees</strong></td>
<td></td>
</tr>
<tr>
<td>T5 <em>I. edulis</em> and</td>
<td><em>I. edulis</em> seedlings and a mixture of <em>Mucuna</em> and <em>Canavalia</em> seeds alternated between <em>T. amazonia</em> seedlings</td>
</tr>
<tr>
<td>cover crops</td>
<td></td>
</tr>
<tr>
<td>T6 <em>I. edulis</em></td>
<td><em>I. edulis</em> seedlings were interplanted with <em>T. amazonia</em></td>
</tr>
<tr>
<td>T7 <em>G. sepium</em></td>
<td>Stake cuttings of <em>G. sepium</em> were interplanted with <em>T. amazonia</em></td>
</tr>
<tr>
<td>T8 <em>I. edulis</em> and</td>
<td>These two legume trees alternated with seedlings of <em>T. amazonia</em></td>
</tr>
<tr>
<td><em>G. sepium</em></td>
<td></td>
</tr>
</tbody>
</table>
T8, the most complex treatment with three woody species.

2.5. Experimental design

The bowl-shaped terrain ("amphitheater") where we established the experiment was surveyed by conventional means in 1993 and mapped at 2 m contour intervals. A second survey of the plot corners was superimposed on this contour map. We used ArcGIS 8.3 to create a 3-D map with blocks and plots draped over the terrain (Carpenter et al., 2004).

We established a randomized block design with each treatment represented in all five blocks, for a total of 40 treatment plots (Fig. 2). Blocks were based primarily on visual impressions of slope and severity of erosion. Factors kept constant within each block included the degree of slope, slope aspect, terrain type, degree of erosion and soil color. Blocks 1 and 2 (B1 and B2) were steep and intersected with cattle trails. Block 3 was relatively flat land at the foot of both B1 and B2. The terrain of B4 consisted of gently rolling hills. Block 5 was relatively flat but contained deeply eroded parts (Fig. 3).

Each plot measured 24 m × 26 m; all 40 plots covered a total area of approximately 2.5 ha. *T. amazonia* seedlings were planted at 3 m × 3 m spacing (Fig. 1). Although each plot had 93 planting sites, adjacent plots shared the outermost border. Therefore, the entire experiment began with 3480 seedlings. To reduce potential influence of edge effects on our analysis of treatment effect on tree growth, we eliminated height data from the two outer borders of trees in each plot, analyzing only the core 45 *T. amazonia* trees. Thus, for treatment analyses, the sample size was 1800 trees.

2.6. Measurements

For each plot we estimated erosion. Three field workers judged the degree of erosion in each plot independently based on depth and extent of cattle

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**Legend**

- **Block 1**
- **Block 2**
- **Block 3**
- **Block 4**
- **Block 5**

Fig. 2. Experimental layout showing five blocks and nine treatments. Numbers 1–8 represent the eight treatments described in Table 1. The ninth treatment is natural regeneration, not discussed in this paper.
Fig. 3. Treatment differences in eight-year tree heights. Tukey groups are indicated by lower-case letters below each bar.

trails. We assigned each plot a value from 1 to 10, 10 representing the most severe erosion. We then averaged the three values to obtain a single mean for each plot. Although these measurements were subjective, scores were consistent among the three judges and varied by more than two points in only one plot.

Prior to outplanting in July–September 1993, we collected a soil sample bulked from 10 locations within each plot. The soil laboratory at the Centro para Investigaciones Agronomicas of the University of Costa Rica analyzed these 40 samples for nitrate and ammonium (colorimetrically) and extractable phosphate by both Modified Olsen and resin membrane (Cooperband et al., 1994) methods.

Various measurable factors reflect overall tree performance: height, diameter, health and survival. We determined their intercorrelations to help us determine the best variable to analyze. We measured height and diameter at 122 cm (dbh) of T. amazonia in 2001, 8 years after outplanting. We also recorded tree deaths and judged the overall health of trees in 2001. Three field assistants scored each tree’s health according to a subjective scale from 0 to 5. Judgments were based on overall appearance of the tree, including leaf color, density of leaves, robustness of trunks and branches, insect damage and leaf spotting by fungal attack. We also considered condition of the apical meristem because in some cases the central trunk had died back several nodes. The scale represents the following conditions:

- 0: dead
- 1: appeared to be dying
- 2: showed problems such as die back, few leaves, major insect or fungal damage
- 3: average
- 4: very good
- 5: unusually healthy trees

2.7. Statistical analyses

We used SYSTAT 10 and SPSS to perform our analyses. We used Pearson’s test to correlate height and diameter, and Spearman’s tests to determine the correlations between height, health and survival. We based our calculations of survival on the total sample of 3484 trees, whereas correlations between diameter, health and height were based on surviving trees (n = 3215). For tests of block and treatment effects on height, we used two-way ANOVAs without replication on the 1668 core trees surviving to 2001. We used Tukey H.S.D. multiple comparison tests to distinguish groups at alpha = 0.05.

We expected that spatial heterogeneity of growth would occur not only because of treatment effects but also by differences among blocks in erosion and soil N and P. To test our predictions, we performed a multiple regression on tree height as a function of all four N and
P measurements (n = 40 plot means based on the full sample sizes) to determine which factors were the best predictors of tree growth.

Finally, to determine differences between blocks in these factors that could have caused spatial differences in tree growth, we applied one-way ANOVAs on erosion indices and initial soil N and P with block as the factor. Where factors differed significantly between blocks, we looked for patterns across blocks in each factor that reflected the pattern of tree growth across blocks.

3. Results

3.1. Correlation between response variables

All four response variables (height, dbh, survival and health-rank) intercorrelated. Correlation coefficients showed strong relationships between height and diameter (r = 0.92), height and health (r = 0.78), height and survival (r = 0.73) and survival and health (r = 0.86), all significant at P < 0.001. Height clearly reflected other possible measures of performance and is the most common variable used in the literature. Therefore, we selected tree height as the response variable for subsequent analyses of growth.

3.2. Plant survival

Average survival of T. amazonia after 8 years was 92% overall and 93% among core trees. Survival rate of interplanted legumes differed. After the first 2 years, 97% of I. edulis trees had survived (n = 15 plots; Nichols et al., 2001) and survival continues to be high. Conversely, only 5–48% of G. sepium had survived to 1996 (n = 10 plots), when mortality leveled off. Herbaceous legumes exhibited low survival and growth (see Nichols et al. (2001) for discussion of this result).

3.3. Block and treatment effects on height of T. amazonia

Growth of T. amazonia differed significantly by block and treatment (Table 2). The Tukey post-hoc test for block showed that growth was least in B5, B2 and B1 and highest in B4 and B3 (Table 3). The Tukey post-hoc test for treatment differentiated three treatment groups (Fig. 3). The only treatments that grew significantly taller than controls were T6 and T8. No treatments grew significantly less than controls.

3.4. Spatial heterogeneity in growth

Regressions of tree heights that included all 40 blocks showed that tree growth was negatively affected by erosion (r² = -0.28, P = 0.000). On the other hand, growth was positively affected by initial concentrations of nitrate (r² = 0.36, P = 0.025) and phosphate (r² = 0.34, P = 0.030). Our two methods of measuring available P, resin membrane and Olsen, correlated with each other (r = +0.85). However, only membrane P correlated with tree growth (P = 0.03).

Significant effects on growth were also indicated by a multiple regression with all four soil nutrient variables (NH₄, NO₃ and both Olsen and membrane PO₄). The regression including all four variables was significant (r² = 0.253, P = 0.033). Both forward and backward stepwise regressions indicated that nitrate was the best predictor of tree growth (r² = 0.10, P = 0.025).

Therefore, if erosion and soil nutrients differed across the five blocks in the same manner as tree growth, they could account for the block effects. Among all soil variables, the only one that varied

<table>
<thead>
<tr>
<th>Block</th>
<th>N</th>
<th>Subset</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>323</td>
<td>344.0</td>
</tr>
<tr>
<td>2</td>
<td>345</td>
<td>354.7</td>
</tr>
<tr>
<td>1</td>
<td>340</td>
<td>380.1</td>
</tr>
<tr>
<td>4</td>
<td>323</td>
<td>433.6</td>
</tr>
<tr>
<td>3</td>
<td>337</td>
<td>474.1</td>
</tr>
</tbody>
</table>

Mean heights (cm) of T. amazonia are indicated.

<table>
<thead>
<tr>
<th>Source</th>
<th>d.f.</th>
<th>Mean-square</th>
<th>F-ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>4</td>
<td>1,004,480</td>
<td>15.64</td>
<td>0.000</td>
</tr>
<tr>
<td>Treatment</td>
<td>7</td>
<td>445,587</td>
<td>6.94</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>1,668</td>
<td>64,231</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Two-way ANOVA with block (n = 5) and treatment (n = 8) as factors and height (cm) of T. amazonia as the response variable (type III)
across the five blocks in the same pattern as tree growth was erosion. The inverse of erosion mirrors tree growth (Fig. 4).

4. Discussion

4.1. Correlation between response variables

Although not surprising, the strong correlations between height, diameter, health and survival warranted our use of height as the major response variable in our analyses. Had, for example, height and diameter not correlated, we would have used calculated volume as our response variable.

4.2. Treatment effects on growth of *T. amazonia*

Treatments with interplanted *I. edulis* (T6) and with mixed legume trees (T8) grew the best. The treatments with interplanted herbaceous legumes (T3 and T4) grew the least but not significantly less than controls.

One of the most notable results of this analysis is that legume trees can act as nurse trees for *T. amazonia* if the nurse trees grow well. The growth and survival of *I. edulis* was consistently good, whereas that of *G. sepium* was erratic. The legume trees, especially *I. edulis*, through association with N-fixing bacteria may have provided additional N to *T. amazonia*. Possible mechanisms are currently under investigation.

The fact that fertilizer did not improve tree growth has important implications for reforestation in this landscape. Fertilized trees (T2) grew well in our experiment during the first 2 years, but their advantage over controls disappeared by the third year (Nichols et al., 2001). This analysis shows that the fertilized treatment continued to do no better than controls after 8 years. This result is surprising in light of the positive effects of initial soil nitrate and phosphate on subsequent tree growth. We used inorganic fertilizer in the ratios of 10N:30P:10 K. Apparently the positive effects of N and P in the initial untreated soils reflected some unmeasured factor that favors tree growth.

In 1995, we established another experiment with *T. amazonia* using N, P and K fertilizer in separate treatments. The results independently showed no positive effect of any of these fertilizers on growth of *T. amazonia* (Henriquez and Carpenter, unpublished data). At least one other study showed that phosphorus fertilizer had a negligible effect on native tree growth in wet tropical soils (Davidson et al., 1998). We suggest that managers of native tropical tree plantations carefully evaluate their need of inorganic fertilizer. If this result could be widely disseminated among farmers of the region, wasted investment on fertilizer could be avoided.

4.3. Changes from 4-year to 8-year heights

The patterns that have greatest significance for land management began to emerge early (Nichols et al., 2001). After only 4 years of growth, the treatment with *Inga* alone (T6) was significantly better than controls. The treatment with mixed legume trees (T8, including both *Inga* and *Gliricidia*) had the second-highest mean but was not yet significantly different than controls. Four additional years of growth accentuated the patterns, and T8 became significantly different than controls.

4.4. Block effect and environmental heterogeneity

Highly significant block effects showed that trees in different parts of the amphitheater grew at different rates, and suggested that one or more of the characteristics upon which we based our blocking influenced growth. Erosion seems to be the most important of all soil factors that we measured. Not
only did our erosion index explain more variance than any other factor, but the pattern of mean erosion values across blocks mirrored the pattern of mean tree growth. Other factors also explained some variance in growth, especially \( \text{NO}_3 \) and extractable \( \text{PO}_4 \). However, their patterns across blocks did not reflect mean growth as well as erosion: erosion pattern was the inverse of growth pattern (Fig. 4).

One of the most interesting comparisons between results after 4 years and after 8 years was the influence of soil factors. Erosion negatively affected growth after 4 years, but none of the measured soil factors had effects at that time (Nichols et al., 2001). Why would the effect of soil chemistry require four more years to emerge?

We can only speculate because our experiment was not designed to explain these effects. Perhaps the positive effects of nitrate and phosphate initially occurred below-ground in the establishment of root systems and did not translate into tree height until later. After 4 years, canopies had not closed in any plots, but after 8 years many plots had closed canopies. Resultant light competition in a closed canopy might shift resource allocation away from below-ground growth and toward investment in height (Falster and Westoby, 2003; King, 2003; Huante et al., 1998).

5. Conclusions

A major goal of this research is to determine whether planting hardy trees, such as \( T. \text{amazonia} \), on heavily degraded and eroded soils can eventually catalyze reforestation. We found considerable spatial heterogeneity in growth of trees in different treatments. This species grew well in less degraded areas and is potentially a good tree for initiating regeneration on farms that are not too severely eroded.

Despite spatial heterogeneity of tree growth, certain treatments had positive or negative effects on \( T. \text{amazonia} \) regardless of the site in which they were planted. Most importantly, the interplanting of \( I. \text{edulis} \) showed consistently positive results. This pattern was established after only 4 years of growth, but became more pronounced after 8 years. We expected, a priori, that where legumes grew well, they would positively influence growth of \( T. \text{amazonia} \). \( \text{Inga} \) grew better than \( \text{Gliricidia} \), which grew better than herbaceous legumes. As expected, the growth of \( T. \text{amazonia} \) reflected this order.

Initial soil nitrate and phosphate in the field was associated with improved growth of \( T. \text{amazonia} \). Despite these relationships, the results of this experiment continue to suggest that fertilizer is wasted investment for plantations of \( T. \text{amazonia} \).

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http://earthobservatory.nasa.gov/Library/Deforestation/deforestation_2.html.


