Intercropping legume trees with native timber trees rapidly restores cover to eroded tropical pasture without fertilization

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Abstract

As tropical deforestation progresses, increasing areas of land are being degraded through erosion, overgrazing and other processes, leading subsequently to soil infertility and loss of agricultural productivity. Reforestation is a potential way to rehabilitate some of these lands. We planted a commercially valuable native timber species on a degraded pasture in southwestern Costa Rica to test methods of forest establishment that would enhance tree growth without inorganic fertilizer and provide diverse economic and ecological benefits. In addition to an unmanipulated control and fertilized plots, we mixed the timber tree (\textit{Terminalia amazonia}) with two species of nitrogen-fixing trees, with cover crops, or with edible beans. In the beans treatment, height growth of \textit{T. amazonia} at the end of 4 years was significantly lower than in any of the other treatments, and bean production was poor. In the first year fertilized trees grew significantly faster than in all the other treatments. At 2 years, fertilized trees were still significantly taller than in six of seven other treatments. The cover crops did not establish and one of the two legume trees suffered high mortality. Fastest height growth occurred when \textit{T. amazonia} was interplanted with legume trees, especially \textit{Inga edulis}. Plots with \textit{I. edulis} interplanted with \textit{T. amazonia} closed canopy first, saved effort in hand-weeding, and provided large amounts of litter biomass as well as edible fruit pods. Block effects were large and were probably related to unmanipulated factors with which growth in plots correlated, in particular, degree of erosion and plot topography. Our results showed that fertilizer is wasted investment on this site because \textit{T. amazonia} grows well with minimal input even on eroded land. Importantly, timber trees in species-diverse plantations can perform at least as well as in monocultures. The more diverse systems provide ecological benefits including nitrogen fixation and multiple products for humans. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: \textit{Terminalia amazonia}; \textit{Inga edulis}; \textit{Gliricidia sepium}; \textit{Mucuna}; \textit{Canavalia}; Costa Rica; Tropical timber trees; Tropical legumes; Inorganic fertilizer; Intercropping; Tropical plantations; Mixed-species plantations; Native timber trees

1. Introduction

Recent rates of loss of humid tropical forests have been estimated at between 13.7 (FAO, 1997) and 15.4 million ha per annum (Whitmore, 1998). Deforestation
in the humid tropics removes protective vegetative cover and is often associated with building roads, logging, planting annual crops, and other activities that disturb the soil (Solorzano et al., 1991). As a result, much land is losing its productive capacity and can no longer be used (Solorzano et al., 1991). A growing challenge in these regions is to find ways to restore degraded lands to productive use.

Grainger (1988) estimated that there were some 758 million ha of degraded land in the tropics with potential for reforestation, and this number would have grown with advancing deforestation. One method to convert unproductive land to productive forestry systems is to use tree species that are tolerant of the degraded conditions. Our ultimate goal is to enhance the growth rate of a native timber tree on a degraded pasture while restoring ground cover, thereby reducing erosion as well as minimizing time to timber harvest. Our goal in this study is to develop diverse forestry systems that could potentially provide the landowner with more than one product and that will be of more immediate value than timber alone. Examples of such products additional to timber might be firewood, fruit, or even annual crops while the trees are still too small to produce shade.

Both woody and herbaceous legumes can provide additional products for the landowner as well as restore soil fertility and litter cover. Many species produce edible seeds and legume trees often have good fuel wood. Furthermore, nitrogen-fixing legumes may enrich the soil and in some cases seem to stimulate growth in mixtures with other plants (MacDicken, 1994). The use of mixtures of N-fixing and non-N-fixing trees in plantations has been studied in several combinations of tree species (MacDicken, 1994). Associations in which the non-N-fixing tree has benefited include both temperate and tropical examples. In the temperate zone, Douglas-fir (Pseudotsuga menziesii) apparently grows faster in mixtures with red alder, Alnus rubra (Tarrant, 1961). Lobolly pine, Pinus taeda, grows faster when interplanted with black locust (Robinia pseudoacacia; Groninger et al., 1997). In the tropics Eucalyptus saligna yielded up to 60% more wood when mixed with Albizia falcata (DeBell et al., 1985). In this system mixed stands produced more biomass, contained larger above-ground nutrient pools, and cycled more nutrients through litterfall than monocultures of either species (Binkley et al., 1992). Khanna (1997) found that 25 and 33 months after planting, eucalypt heights, DBH, basal area and volume were positively correlated with the presence of acacia. In tropical India intercropping the legume tree Leucaena leucocephala with teak (Tectona grandis) increased both height and diameter growth in teak, as well as improving the N and phosphorus status of the soil (Ng et al., 1983; Kumar, 1998).

Herbaceous legumes have been used as ground covers in tree-crop plantations in the humid tropics (Pushparajah, 1982; Nair, 1993). Rubber and oil palm plantations use kudzu, Pueraria phaseoloides, for weed control or green manure in commercial plantings in southeast Asia (Ikram et al., 1994) and Central America (Ortiz and Fernandez, 1992). Nwonwu and Obiaga (1988) used three types of N-fixing cover crops in plantations of Pinus caribaea in Nigeria and compared costs and benefits with a hand-weeded treatment. They concluded that, though growth of trees did not differ significantly among the treatments, the cost per ha of hand-weeding was lower when cover crops were used. In contrast, Alley et al. (1999) found that when three timber tree species were combined with N-fixing cover crops in temperate plantings, they did not perform as well as when grown where spot spraying with glyphosate had been employed.

We chose a native timber tree to be interplanted with two native species of legume trees, edible beans, or legume cover crops to determine what combination(s) provide(s) the greatest tree growth, alternative products, and other benefits. Our goals were:

1. Determine if growth of Terminalia amazonia is sufficient in degraded soils for this species to be used in restoration or plantation forestry on eroded pastures.
2. Test whether this timber tree grows as well when interplanted with legumes as when fertilized with inorganic fertilizer.
3. Determine which legume species grow well enough in degraded soils to yield alternative products when used in a polycultural agroforestry system with T. amazonia established on eroded pasture.
4. Determine if interplanting cover crops or legume tree saves labor in hand-weeding.
2. Materials and methods

2.1. Site description

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 is "tropical premontane rainforest". Much of the region is steep, subject to erosion, and inappropriate for annual crops or pasture.

Soils on the farm 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 19-28%, and sand and sand-sized particles 48-64%. These soils are acid, phosphorus-fixing and infertile — more so after erosion removes topsoil (Carpenter et al., 2001).

Much of the county of Coto Brus was still natural forest after World War II. During the 1950s and 1960s, the forest where the farm is located was cleared and converted to coffee plantations. Approximately 20 ha of the 25 ha on the farm were converted to pasture in 1978 by planting the introduced, exotic grass species Paspalum nicaraguense, Brachiaria sp. and Melinis minutiflora (Poaceae). The first two species now dominate. Beef production on the farm by 1990 was half what it was in the 1970s and some 50% of the land surface was bare because of deeply incised cattle paths across the slopes. In 1992 the farm was acquired for long term research and 5 ha were fenced from cattle grazing in 1993 for this experiment.

2.2. The trees

_T. amazonia_ (Combretaceae) was our focal timber species. It ranges from Mexico through Central America and from the Caribbean to Brazil. Although _T. amazonia _has not been widely established in plantations, we chose it for several reasons. Its timber is highly valued and it appears to have potential for good growth on a wide range of sites in the humid tropics (Gonzalez and Fisher, 1994; Nichols, 1994). Nichols et al. (1997) measured heights and diameters in 25 plantations on farms in Costa Rica and found a high mean survival rate (88%) and mean heights of 332 cm at 3 years, even though nine of the plantations had no weed control. The tallest individual tree was 10.9 m tall, with a dbh of 11.0 cm. Furthermore, in the four plantations with the best growth the soil pH ranged from 4.4 to 4.9 and P levels ranged from 1.68 to 2.15 mg/g. These conditions were similar to those on our study site.

Haggar et al. (1998) reported on the relative performance of 80 tree species planted in northeastern Costa Rica at a lowland humid site. At 6 years, _T. amazonia_ was ranked 12th, with a mean height of 13.9 m and a mean diameter of 15.4 cm. Two previous studies (Nichols et al., 1997; Henriquez and Carpenter, in preparation) suggested that _N_ might limit the growth rate of this species. As a result, we predicted that interplanting _N_-fixers might increase its growth rate.

All of the legumes that we selected for interplanting have alternative uses for local people, such as fuel wood or fodder. We chose _Inga edulis_ Mart. (Fabaceae) as one of the legume trees to mix with _T. amazonia_. The genus _Inga_ contains up to 300 species, and is native to and widespread in Latin America (Lawrence et al., 1995). _I. edulis_ is one of the most popular shade trees for coffee and cacao plantations in the humid neotropics, and in southwestern Costa Rica is commonly planted over coffee at spacing down to 2 m × 2 m (Nichols, 1990). This legume produces both an edible fruit and fuel wood in addition to shade and litter for the plantations (Lawrence et al., 1995). Among a group of 25 species of legume trees planted in northeastern Costa Rica, _I. edulis _was third in production of stem volume at 3 years and was among those fast-growers with the highest nitrogenase activity (Tilki and Fisher, 1998). Palm and Sanchez (1991) noted that _I. edulis _leaves are relatively high in polyphenolics in comparison to another frequently used agroforestry legume, _Erythrina _sp. Therefore, the leaves of _I. edulis_ are slower to decompose, which may be an advantage in situations in which the goal is to improve nutrient cycling and levels of _N_ in soil organic matter. In fact, in a study in northeastern lowland Costa Rica, the upper 15 cm of soil beneath
plantings of *L. edulis* were found to have improved over 3 years in several aspects, including total kjeldahl N, soil organic C, surface bulk density, and extractable P (Fisher, 1995). A final benefit of this species is that *L. edulis* attracts a variety of pollinators and seed dispersers (Lawrence et al., 1995), thereby contributing to biodiversity of the system.

We chose *Glicicidia sepium* (Jacq.) Walp (Fabaceae) as a second legume tree for interplanting. This tree is one of the major N-fixing agroforestry species in the humid tropics (Nair, 1993). It is used as shade over coffee, cacao, and tea, in live fences, and in alley cropping, and produces firewood, fodder, and timber usable for furniture and tool handles. *G. sepium* produces high-quality green manure: pruning from one study in Nigeria yielded 169 kg N, 11 kg P, 149 kg K, 66 kg Ca, and 17 kg Mg per ha per year (Kang et al., 1989). It can be propagated from stem cuttings as well as from seed. *Glicicidia* leaves have traditionally been used as rodenticide and pest repellent (Glover, 1989), so their proximity to our timber tree might confer some neighborhood defense.

2.3. The herbaceous legumes

For interplantings with herbaceous legumes, we chose edible beans (*Phaseolus vulgaris* cv. 'Chimbolo') and two species of cover crops, Velvetbean, *Mucuna pruriens* (white seeded) and Jack Bean, *Canavalia ensiformis*, all Fabaceae. The edible bean “Chimbolo” is considered a traditional variety. *Mucuna* is moderately tolerant of soil acidity (Hairiah et al., 1993), and is an important green manure and weed suppressor in corn production in Central America (Buckles et al., 1998). It has been used to reclaim land after colonization by Imperial grass in SE Asia (Hairiah et al., 1993), where it is native. *C. ensiformis*, a native of the New World, is cultivated throughout the tropics as a green manure crop, as soil cover to prevent erosion and for forage. It is intercropped with coffee, rubber, cacao, citrus and coconut (Duke, 1981). It is tolerant of soil acidity (Torrealba et al., 1998) and considered to be more drought-tolerant than *Mucuna* (Duke, 1981).

2.4. Treatment rationale

The treatments are briefly summarized in Table 1. In all plots we kept density of *T. amazonia* constant and hand-weeded 0.5 m radii around surviving trees when necessary.

The control, T1, consisted of *T. amazonia* seedlings with no manipulation except weeding. In the fertilizer treatment, 50 g of 10% N, 30% P, 10% K was mixed with the loose soil in the bottom of the planting hole. In year 2 we applied 30 g of “Formula Completa” — 18% N, 5% P, 13% K, 6% MgO, 2% B, and 3.7% S — in three or four holes dug in the rooting zone. In years

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight experimental treatments, T1-T8</td>
</tr>
<tr>
<td>No interplantings</td>
</tr>
<tr>
<td><strong>T1</strong> Control</td>
</tr>
<tr>
<td><strong>T2</strong> Fertilized</td>
</tr>
<tr>
<td>Herbaceous legumes interplanted</td>
</tr>
<tr>
<td><strong>T3</strong> Edible beans</td>
</tr>
<tr>
<td><strong>T4</strong> Cover crops</td>
</tr>
<tr>
<td>Legume trees interplanted</td>
</tr>
<tr>
<td><strong>T5</strong></td>
</tr>
<tr>
<td><strong>T6</strong> Inga</td>
</tr>
<tr>
<td><strong>T7</strong> Glicicidia</td>
</tr>
<tr>
<td><strong>T8</strong> Mixed</td>
</tr>
<tr>
<td><em>T. amazonia</em> seedlings planted at the center of 1 m diameter cleared spots</td>
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<tr>
<td>50 g of 10-30-10 applied in the planting hole in year 1; the same amount of <em>Formula Completa</em> (high N) applied in years 2-4 in three to four holes dug in the rooting zone</td>
</tr>
<tr>
<td>Seeds of <em>Phaseolus vulgaris</em> sown in the area between rows of trees in November of each of the first 3 years, beans harvested the following February</td>
</tr>
<tr>
<td>Seeds of the N-fixing cover crops <em>Mucuna pruriens</em> and <em>Canavalia ensiformis</em> sown among the trees each of the first 3 years</td>
</tr>
<tr>
<td><em>I. edulis</em> seedlings and a mixture of <em>Mucuna</em> and <em>Canavalia</em> seeds alternated between <em>T. amazonia</em> (555 <em>I. edulis</em> and 555 spots with the cover crop mix per ha)</td>
</tr>
<tr>
<td>Seedlings of <em>I. edulis</em> interplanted (1111 <em>I. edulis</em> per ha)</td>
</tr>
<tr>
<td>Cuttings of <em>G. sepium</em> interplanted (1111 <em>G. sepium</em> cuttings per ha)</td>
</tr>
<tr>
<td><em>I. edulis</em> and <em>G. sepium</em>; the two species of tree legumes alternated between <em>T. amazonia</em> (555 trees of each legume species per ha)</td>
</tr>
</tbody>
</table>

* Density of *T. amazonia* is constant in all plots at 1111 per ha.
3 and 4 we applied 45 g of Formula Completa in the same manner. These formulas and amounts are those recommended by local foresters. We expected the control (T1) and the fertilizer (T2) treatments to give lower and upper boundaries, respectively, of growth rate in *T. amazonia* and to form the basis for comparing the legume treatments.

In treatment 3 we sowed dry beans (*Phaseolus vulgaris*) using the frijol tapado system (Thurston, 1997) in the area between the rows of tree seedlings. In November of each of the first 3 years, we broadcast the seed into 2 m wide rows of grasses and weeds between the tree seedlings and then cut down the vegetation to form mulch. The system is commonly used in the area for both commercial and subsistence production of dry beans (Rosenmeyer et al., 1999). We harvested, dried, and weighed the beans the following February. This treatment tested the possibility that ungrazed pasture grasses and weeds might provide enough mulch to produce a bean crop while the trees were still small.

A mix of six seeds of *M. pruriens* and *C. ensiformis* was sown between each pair of adjacent tree seedlings in the rainy season each of the first 3 years. This treatment (T4) tested the possibility that cover crops adapted to acid soils could improve growth of *T. amazonia* and/or reduce labor of hand-weeding the tree seedlings.

In the following treatments with N-fixing trees, we planted the N-fixing tree 1.5 m from adjacent *T. amazonia* trees. These treatments tested the expectations that:

1. interplanted legume trees would hasten canopy closure, reducing labor input for hand-weeding; and presumably providing earlier protection against erosion;
2. legume trees would provide useful products alternative to and sooner than timber;
3. interplanting legume trees would increase height growth in the timber tree;
4. interplanting would increase habitat complexity, which might reduce pest attack on the timber tree.

In one treatment (T6) we interplanted 3-month old seedlings of *I. edulis* among *T. amazonia* (1111 *T. amazonia* per ha and 1111 *I. edulis* per ha). Treatment 7 was identical but we substituted 1.5 m long stake cuttings of *G. sepium* as the legume. We treated and planted the cuttings according to long-established methods of tropical zone farmers (Glover, 1989). This treatment also tested the idea that pesticidal chemicals in the foliage and bark of this legume tree could reduce pest attack on neighboring *T. amazonia* seedlings.

Finally, we established two treatments that increased species diversity and structural complexity of the plots above those in the other interplanted treatments. Diversity and complexity would yield benefits to wildlife by providing better habitat and might reduce pest attack on *T. amazonia*. In treatment 8 both *I. edulis* and *G. sepium* alternated between *T. amazonia* (Fig. 1), and in treatment 9 *I. edulis* and a mixture of *Mucuna* and *Canavalia* alternated between *T. amazonia*.

2.5. Seed and cutting provenances, planting and maintenance procedures

Seed of *T. amazonia* was collected between the end of May and the end of June 1993 from 14 selected seed trees located within 9 km of the study site between 930–1170 m elevation. Seeds were sown in germination beds at the farm, transplanted to plastic nursery bags at the two-leaf stage and outplanted in September 1993 when they were about 5 cm tall. We replaced seedlings that died within 2 months with seedlings from the same lot in the nursery. Some trees bifurcated or trifurcated; we pruned the weaker stem(s) in April 1995 and February 1996.

*I. edulis* seeds came from three trees in Los Planes, 7 km E of the study farm. They germinated in nursery bags in May 1993 and were outplanted in July 1993. We hand-weeded seedlings by machete one time, in October 1993. We took stake cuttings of *G. sepium* in April 1993 from healthy trees in Lourdes 13 km N of the farm and laid them horizontally for several days until callus formed. Then we stored them vertically until ready to plant. We replaced cuttings that died with new cuttings in March 1994. Stakes needed no weeding.

We procured seed of the edible bean locally and seeds of *Mucuna* and *Canavalia* from CIDICCO (Centro Internacional de Informacion sobre Cultivos de Cobertura) in Honduras. For *Mucuna* and *Canavalia* we dug weeds from a m diameter area at each planting site upon planting the seeds but did not subsequently weed. We applied no fertilizer. The herbaceous legumes were replanted in 1994 and 1995.
2.6. Experimental design and measurements

In July 1993 we established five blocks, each treatment represented once in each block, for eight plots per block. We attempted to place each block within the terrain so that certain environmental characteristics were as similar as possible among the eight plots of a given block. The characteristics upon which we based our blocking were degree of slope, slope aspect, terrain type, degree of erosion, and soil color. For each plot we only characterized the area of the 45 central planting locations ("core" — Fig. 1). Using a clinometer we measured the slopes along a 2 m long fall line centered at all 45 T. amazonia seedlings in the
Table 2
Soil characteristics of five experimental blocks in 1993

<table>
<thead>
<tr>
<th>Block</th>
<th>pH (water)</th>
<th>P&lt;sup&gt;2&lt;/sup&gt; (mg/l)</th>
<th>OM&lt;sup&gt;3&lt;/sup&gt; (%)</th>
<th>Al (% saturation)</th>
<th>CEC cmol (+)/Kg</th>
<th>NO&lt;sub&gt;3&lt;/sub&gt;&lt;sup&gt;4&lt;/sup&gt; (ppm)</th>
<th>NH&lt;sub&gt;4&lt;/sub&gt;&lt;sup&gt;6&lt;/sup&gt; (ppm)</th>
<th>Ca&lt;sup&gt;9&lt;/sup&gt; cmol (+)/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean values by block</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.8 a</td>
<td>0.4 a</td>
<td>4.7 a</td>
<td>45.6 c</td>
<td>9.7 b</td>
<td>43.8 a</td>
<td>5.8 a</td>
<td>3.8 a</td>
</tr>
<tr>
<td>2</td>
<td>4.9 a</td>
<td>0.7 a</td>
<td>5.6 a</td>
<td>27.6 b</td>
<td>13.5 c</td>
<td>46.3 ab</td>
<td>6.4 ab</td>
<td>7.4 b</td>
</tr>
<tr>
<td>3</td>
<td>5.2 b</td>
<td>2.9 b</td>
<td>5.4 a</td>
<td>16.8 a</td>
<td>12.5 bc</td>
<td>56.8 c</td>
<td>7.9 b</td>
<td>8.1 b</td>
</tr>
<tr>
<td>4</td>
<td>4.9 a</td>
<td>2.6 b</td>
<td>7.3 b</td>
<td>34.2 bc</td>
<td>6.6 a</td>
<td>55.9 c</td>
<td>7.8 b</td>
<td>3.1 a</td>
</tr>
<tr>
<td>5</td>
<td>5.2 b</td>
<td>3.0 b</td>
<td>7.0 b</td>
<td>22.8 a</td>
<td>5.9 a</td>
<td>52.3 bc</td>
<td>7.9 b</td>
<td>3.2 a</td>
</tr>
</tbody>
</table>

<sup>a</sup> The order of average growth rates by block was: 3 > 4 = 2 > 1 = 5.
<sup>b</sup> Modified Olsen.
<sup>c</sup> Walkley–Black.
<sup>d</sup> Colorimetric.
<sup>e</sup> KCl extraction, atomic absorption.

core and averaged these 45 values to give the plot mean. We measured slope aspect with a compass in the core of each plot. For terrain, we judged whether each plot fit one of four categories: steep, flat, valley, or hilltop. For erosion, we established a subjective scale from 1 to 10 with 10 representing the deepest, most extensive erosion. Three people independently scored the core of each plot for erosion and these scores were averaged. Only in one plot did our scores differ by more than two points. Tables 2 and 3 describes the soil and slope characteristics of the five blocks.

At the beginning of the experiment we collected soil samples to be analyzed chemically by the Centro de Investigaciones Agronómicas (CIA) of the University of Costa Rica. With an Oakfield core sampler, Model K, we took 10 soil cores per plot at the following positions in the plot (Fig. 1): between planting sites 10-18-19; 28-29-37; 47 (two spots at the center of entire plot); 54-62-63; 31-32-40; and 11-24-25. These 10 positions form an X across the entire plot.

For each plot we split each soil core into 0–15 and 15–30 cm depths. We combined shallow segments in one bag and deep segments in another for a total of 10 segments for each depth for each plot. We labeled, froze and transported all samples to CIA, where each was homogenized and analyzed.

Each plot measured 24 m × 26 m such that the entire experiment occupied about 2.5 ha. In every treatment-plot we planted 93 T. amazonia seedlings at 3 m × 3 m spacing in hexagonal arrays (Fig. 1).

We took the following measurements:

- height of T. amazonia every year, diameter at breast height (dbh) in years 2–4, 1995–1997;
- number and biomass of harvested beans in 1994–1996;

Table 3
Slope and erosion characteristics of five experimental blocks

<table>
<thead>
<tr>
<th>Block</th>
<th>Aspect</th>
<th>Plot terrains&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Slope (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Erosion&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 steep</td>
<td>West</td>
<td>S8</td>
<td>58 a</td>
<td>7.4 a</td>
</tr>
<tr>
<td>2 steep</td>
<td>South</td>
<td>S8</td>
<td>58 a</td>
<td>7.5 a</td>
</tr>
<tr>
<td>3 alluvial</td>
<td>Flat, mixed aspects</td>
<td>F5, S1, M2</td>
<td>25 b</td>
<td>3.1 c</td>
</tr>
<tr>
<td>4 hilly</td>
<td>Southeast</td>
<td>H4, S3, V1</td>
<td>28 b</td>
<td>5.0 bc</td>
</tr>
<tr>
<td>5 cut up</td>
<td>South</td>
<td>S5, H1, F1, V1</td>
<td>31 b</td>
<td>6.6 ab</td>
</tr>
</tbody>
</table>

<sup>a</sup> Key to terrain codes: S: steep, F: flat, H: hilly, V: valley, M: mixed. Numbers indicate how many of the eight plots in each block are described by each terrain type.
<sup>b</sup> Values are averages of the eight plots per block. One-way ANOVA P = 0.0000.
Dbh measurements in *I. edulis* could only be made once a tree reached 122 cm in height, so we have no dbh data at 1 year (1994). *I. edulis* heights were not measured after 2 years as this species produced multiple stems, forming arching branches that spread horizontally. However, at 2 years (1995) height and dbh correlated strongly (*r* = 0.91, *P* < 0.000). Therefore, dbh alone is a good measure of growth in this species.

We took no measurements of *G. sepium* before year 2000 because both height and dbh were influenced greatly by original size of the stake cutting. Since these sizes varied, measurements would have been arbitrary during early growth.

### 2.7. Statistical analyses

We used a General Linear Model to test for differences among blocks in soil characteristics. We used the a posteriori Tukey HSD Multiple Comparison for all variables at an alpha level of *P* = 0.05 to determine significantly different groups of Blocks for each soil characteristic. In all analyses of *T. amazonia* growth we included only data from the central core of 45 trees in each plot (see Fig. 1) to eliminate any edge effects or influences from neighboring treatments. We used SPSS to perform Two-way ANOVAs without replication, with Tukey tests for means separation at an alpha level of *P* = 0.05. Tukey tests were a conservative approach because we had a priori predictions about the differences among treatments.

### 3. Results

#### 3.1. Survival and growth of interplanted species

*Inga* survived well (97%) but grew slowly the first 2 years (mean of five T6 plots = 1.0 cm dbh 1993–1995). Then growth rate increased greatly, mean = 3.5 cm dbh 1995–1997 despite several severe prunings during that interval. Competition with *T. amazonia* became severe by October 1995, so we pruned *I. edulis* that month and again two more times before the final measurement of *T. amazonia* 4 years after planting, in August 1997. We left prunings on the ground, but they were sufficiently substantial to have provided a family with fuel wood upon pruning.

*G. sepium* suffered high mortality. Even though we replaced dead cuttings 9 months after the initial planting, mortality ranged from 52 to 95% by 1996. However, the surviving stake cuttings eventually produced robust, low trees under the *T. amazonia* canopy. Extensive networks of *G. sepium* roots with nodules occurred in the topsoil in the *G. sepium* plots in which at least one-quarter of the cuttings survived.

The herbaceous legumes (T3, T4, T5) did very poorly. Although the cover crops germinated well and produced a few leaves, no plants were detected within a few months after sowing in any year. In T3 fewer and smaller beans were produced than were sown (mean 26 versus 61 kg/ha) in the first year. Production improved somewhat subsequently, 82 kg/ha on average in year 2 and 86 kg/ha in year 3, with the same input as before. Average frijol tapado yields in Costa Rica are reported at 200 kg/ha.

#### 3.2. Survival and growth of *T. amazonia*

Overall survival of *T. amazonia* 2 months after outplanting from the nursery to the field was 98%. After the first dry season when seedlings had been in the field for 10 months, overall survival was still high, 91%. Height-growth differed significantly in the different treatments (Table 4). At the second measurement, 10 months after outplanting, fertilized trees, T2, had significantly higher height growth than trees in any of the other treatments (Fig. 2). At 2 years the difference was still significant. However, this difference disappeared in the third year and the fertilized trees were not significantly taller than those in any of the other treatments except those in treatment 3. Growth rate of trees in the frijol tapado treatment, T3, was significantly less than those in all other treatments. After 4 years this disadvantage was still significant. By the fourth year, *T. amazonia* interplanted with *I. edulis*, *G. sepium*, or a mix of the two (T6–T8)

<table>
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<th>Source</th>
<th>SS</th>
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tended to have the greatest growth and this trend was significant in the case of T6. At 4 years, *T. amazonia* planted with *I. edulis* was 15% taller than trees in the control.

Block effect was large (Table 4), suggesting that one or more of the characteristics upon which we based our blocking influenced growth rate. One block (B3) that had the least erosion and flat, alluvial topography also had the best average growth and the least difference among treatments in growth. This block did not stand out in any of the soil characteristics (Tables 2 and 3). In fact, growth rate across all 40 plots did not correlate with any chemical measure (for example, *P* for OM = 0.93, Ca = 0.99, P = 0.26, Al = 0.33, pH = 0.94). However, growth did correlate with degree of erosion (*R* = −0.51, *P* = 0.001). Although slope and erosion correlated (*R* = 0.70), growth was not correlated with slope (*R* = −0.23, *P* = 0.47).

Because we did not replicate treatments within blocks we could not address block × treatment interactions. Inspection of Fig. 3 suggests that how well a treatment did relative to other treatments may have depended on block. Such interaction would be difficult to disentangle because of so many uncontrolled variables in the field.

### 3.3. Canopy closure and hand-weeding

*I. edulis* survived well, spread horizontally, and produced a mean canopy width of 153 cm after 2 years. By the end of 1995 after 2 years of growth, eight of the 40 plots had closed canopy, four of them being the Inga treatment and the remainder all having *I. edulis* as one of the interplanted species. We compared the labor input of hand-weeding by machete in T1, T2, T6. In the control, T1, the mean person-hours invested per year per plot gradually decreased — 3.8 to 3.5 to 3.3 in 1993, 1995, 1997, respectively, — as *T. amazonia* grew and began to shade the weeds. In the fertilized treatment, T2, mean person-hours began at 3.8 in 1993 upon planting, peaked at 6.0 in 1995 after three successive fertilizations, and declined to 3.8 after 1 year of no fertilization. In comparison, mean person-hours in T6 began high (7.3) in 1993 when we...
Fig. 3. Growth of *T. amazonia* in different treatments in the five blocks. The control was weeded and pruned as in the other treatments but otherwise not treated.
cleared around seedlings, which doubled labor input per plot. By 1995 the Inga treatment had similar labor input as the control (3.25). By 1997 labor input in hand-weeding of T6 had fallen to the lowest of all treatments (2.8).

3.4. Pest and disease damage to *T. amazonia*

In 1994 the timber tree had the following pests: (1) *Pestalotia* sp, a fungus, (2) *Fusarium* sp, another fungus, and (3) *Erwinia* sp, a bacterium. *Pestalotia* left the most conspicuous sign, red spots on the leaves.

We checked degree of herbivore and fungal damage to *T. amazonia* in the control, Inga, and Glicidica treatments in 1996. Little insect damage occurred, but some trees suffered substantial fungal attack. Glicidica reduced neither herbivore damage nor fungal (*Pestalotia*) attack on *T. amazonia* as might be expected from this legume's known pest repellent properties. However, the poor health and low density of surviving cuttings makes this a questionable test of the idea. Fungal attack was significantly higher (*P* = 0.02) in the *I. edulis* treatment (7.5%) than in either the control (3.7%) or the Glicidica (3.2%) treatments.

4. Discussion

4.1. General survival and growth of legumes

Beans and cover crops failed to grow well. The critical level of available P for bean production is 14 ppm Olsen-EDTA (Flor and Thung, 1989). This is much higher than determined in our soils, which registered 0–3.7 (mean 1.6) ppm modified Olsen in our T3 plots. Low available P is considered the most important fertility problem of beans in Latin America (Schwartz and Galvez, 1980).

According to information about the cover crop species, they should have grown well in these soils. Mucuna is moderately acid tolerant (Hairiah et al., 1993), and in Colombia Mucuna deeringiana was able to shade out *Imperator contracta* grass on soils of pH 5.5–6.5 (CONIF, 1987). However, it is sensitive to aluminum reduction of P uptake (Hairiah et al., 1993). In Asia when topsoil was removed due to erosion, Mucuna growth was retarded and the authors concluded that since Mucuna was less Al tolerant than *I. contracta* it would be less effective in land reclamation where the topsoil has been eroded (Noordwijk et al., 1993). Though Canavalia can tolerate acid soil of pH 4.3–6.8, in highly acidic soil growth and grain yield are reduced due to excess Al, P deficiency and low pH (Torrealba et al., 1998). Canavalia did not respond as much to P and liming as Mucuna in a Brazilian Podzol (Rodrigues et al., 1994), and did not respond to P in other studies without lime (Silva and Faria, 1989). In the treatment 4 plots our soil pH was 4.6–5.2 (mean 4.9) and registered 0.8–3.0 (mean 1.7) ppm P by modified Olsen. Percent Al saturation was variable, ranging from 18 to 60%. From our data and the literature we conclude that pH, Al and P availability did not favor growth of either of the cover crops.

As a result, the cover crops seemed to lose in competition with weeds and grasses, which overtopped the slowly growing, newly establishing herbaceous legumes. We did not hand weed because of prohibitive labor input, but weeding might have helped these species.

MacDicken (1994) states that the mean annual temperatures in the native range of *G. sepium* are 20–29°C. Our site is close to the lower end of temperature and this may explain why our cuttings suffered high mortality.

Inga grew well once it passed a 2-year growth lag. A similar growth pattern has been seen in another study in Costa Rica (Nichols personal observation). However, no such lag occurred in a study of 25 legume tree species including *I. edulis*, on similarly acid soils in Costa Rica (Tilki and Fisher, 1998). We are currently testing ideas about causes of the lag in our system. Two of our hypotheses are competition with grass and weeds, and/or time to encounter optimal mycorrhizal fungi. Plots of T6 and T8 closed canopy quickly, produced dense undergrowth, shaded out pasture grasses soon and produced large quantities of harvestable fuel wood.

4.2. Treatment effects on *T. amazonia* growth

High survival of *T. amazonia* was consistent with the findings of Nichols et al. (1997), who found 3-year survival of 88% in 25 plantations, many of which had little maintenance. The control and fertilizer
treatments did not bracket the growth performance of *T. amazonia* as we had expected. The controls did surprisingly well and had the highest growth in one block (B4). Fertilizer, even though applied in each of the first 4 years, did not increase overall growth significantly above that of the control over the long run. Based on these results we can suggest that on sites low in P, fertilization with P would probably provide minimal benefit. Our result was consistent with that of Davidson et al. (1998) showing that 15 native species of tree seedlings did not respond to fertilizer in an Ecuadorian P-fixing tropical soil. Besides wasted investment, fertilizer applied after the initial planting may be detrimental in that it seems to be related to increased effort spent on hand-weeding.

The N-fixing trees took 2 years to establish and therefore would be unlikely to have a positive effect on growth of *T. amazonia* in the first years. *T. amazonia* in all these treatments had faster growth in the final years. Treatment T4 with half density of *I. edulis* showed no better growth than the treatments without N-fixing trees (excepting T3 (beans) of course).

### 4.3. Weed control

Mixtures of *T. amazonia* with N-fixing trees, particularly with *I. edulis*, clearly achieved canopy closure before treatments with no N-fixing trees or with cover crops. With a primary objective of gaining canopy closure as quickly as possible for weed control, the *I. edulis/T. amazonia* mixture could be recommended. It would have the advantage of not requiring further weeding, although pruning or elimination of the *I. edulis* is later necessary to maintain dominance by *T. amazonia* in this dense interplanting. Also, we saw the first pod production in 1995, so this treatment began to provide the added benefit of attracting a variety of pollinators and seed dispersers (Lawrence et al., 1995).

Foresters often recommend complete weed control, including keeping the rows between trees treated with herbicides or mowed (Evans, 1992). But we found that growth was significantly reduced in treatments where we had cut grass and brush in the interrows (*Phaseolus vulgaris* treatment). This treatment exposed the small tree seedlings immediately before and during the dry season, which began in December and ended in March each year. Consistent with this interpretation is the fact that reduction in growth increment disappeared in this treatment in the final year, once the seedlings were well established. An experiment begun on the same farm with *I. edulis* (Rhodes-Conway and Carpenter, 1999; Rhodes-Conway, 2000) demonstrated that reduced growth in tree seedlings in cleared treatments was related to higher soil temperatures during the dry season. Therefore, we recommend that no clearing be done at least 2 months before the dry season, and only recommence once the rains have begun with certainty.

### 4.4. Blocks and environmental heterogeneity

The effect of block on height growth was probably related to unmanipulated factors with which growth correlated, in particular, degree of erosion of plots and their topography. In the block with the best average growth (B3), the ratio between best and worst growth in the eight plots was the smallest — 1.5 — of all the blocks, i.e., growth was even among the plots regardless of treatment. This block was located at the foot of steep, eroded slopes and probably caught topsoil as it washed downslope. In the block with the worst average growth (B5), this ratio was 2.3. The best growth in this poor block occurred in a plot randomly located in an area with the least erosion and the most valley-shaped topography.

We previously demonstrated (Carpenter et al., 2001) that deep erosion on this study site removed mycorrhizal fungi and changed the diversity and composition of their communities. Valleys and depressions on flat topography would collect mycorrhizal spores as they are washed down from the slopes above. In our previous study we found reasonable numbers and the highest diversity of mycorrhizal spores in depressions, as long as there was vegetative cover and roots. Therefore, it is possible that the block with the poorest performance was also the one that had the most impoverished mycorrhizal communities and the one with the best performance had collected spores in the runoff from the slopes above.

Previous studies have shown that topography is important in determining the distribution of tree species in a Costa Rican forest (Clark et al., 1999), although we know of no studies connecting mycorrhizal density, species composition or diversity to the types of trees that grow in rain forest.
Soil chemistry had no effect on *T. amazonia* growth. Consistent with this are the studies on Brazilian Oxisols that show that biological factors such as seed dispersal and predation affect forest restoration more than do soil nutrients (Buschbacher et al., 1988).

5. Conclusions

Our results showed that *T. amazonia* grows well with minimal input even on eroded Ultisols. Importantly, fertilizer proved to be wasted investment in the long term.

When combined with *I. edulis*, the height growth of *T. amazonia* was significantly better than in the control, although with other combinations with N-fixing plants this was not the case. Except in areas eroded bare of all vegetation, *T. amazonia* did especially well when combined with *I. edulis*. This combination of species saved labor in hand-weeding, and *Inga* provided biomass usable as fuel by the third year. These benefits lead us to recommend the combination of *T. amazonia* and *I. edulis* for restoration or plantation forestry on eroded pasture that still retains some grass or weed cover.

However, degree of erosion seemed to be more important in determining growth than the treatments. Interplanting this timber tree with legume trees did not compensate for deep erosion in our study. The worst growth was on the spots eroded bare. Such deep erosion removes most mycorrhizal fungi and causes other chemical and microclimatic changes that are inhospitable to vegetative growth, even when the natural pioneering process of succession is short-cut with intentional restoration efforts.

However, as long as erosion has not removed most living roots, tree cover quickly and effectively establishes on degraded pasture with combinations of *T. amazonia* and *I. edulis*. In such species-diverse plantations these timber trees can perform as well as in monocultures, if not better. Thus, diverse systems can provide products in addition to timber.

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