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Early growth performance of native and introduced fast growing tree species in wet to sub-humid climates of the Southern region of Costa Rica

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Abstract

Early growth performance of six native and two introduced tree species was studied for seven years at 16 sites in the Southern region of Costa Rica. Selected study sites represent a wide environmental gradient that ranges from acid low fertility soils such as Ustic Haplohumults and Typic Haplustults to fertile soils such as Typic Hapludand and Fluventic Eutropepts. Mean annual precipitation ranges from 2600 to 4500 mm and length of dry season from none to more than three months each year. The experimental layout was a randomized complete block design nested within four eco-regions, with all plots on private farms. The size of the experimental plot was 11 × 11 trees planted at a spacing of 3 × 3 m with a sampling plot of 7 × 7 trees. The species included in the initial trials were: *Pinus caribaea* Morelet var *hondurensis* (Barret y Golfari) *and Gmelina arborea* Roxb as the introduced species (from Honduras and southeast Asian regions, both of which benefit from genetic selection), and *Terminalia amazonia* (J. F. Gmelin) Exell, *Vochysia ferruginea* Mart., *Vochysia guatemalensis* Donn. Sm., *Hieronyma alchorneoides* Fr. Allemao, *Calophyllum brasiliense* Cambess and *Schizolobium parahyba* (Vell.) S. F. Blake (collected extensively in this project from indigenous populations from across the Southern region of Costa Rica). All plots were measured annually and data collected for tree height, DBH and mortality. Composited soil samples were taken at three depths in each site to characterize chemical and physical soil properties. In general, the native species were highly responsive to eco-regions, the introduced species much less so. The yield and dominant stand height of the introduced species were higher in acid soils with well defined dry season than the selected native species. As soil nutrient and water supply improved, the differences between introduced and native species decreased in mean stand height and yield. Two species (*Calophyllum brasiliense* and *Schizolobium parabyba)* had more than 80% mortality in almost all plots during the first two years of establishment. The results of this study contrasts with findings obtained in the Northern region of Costa Rica on acid Ultisols (Typic Tropohumult), where at least *Vochysia guatemalensis* and *Vochysia ferruginea* out-competed the best introduced species, *Gmelina arborea* and *Pinus* spp. Results are mainly attributed to the pronounced ustic moisture regime in the Southern region of Costa Rica that is able to be tolerated by *Gmelina arborea* and *Pinus* spp. but not by the selected native tree seedlings.
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Keywords: Tropical tree species; Tropical reforestation; Tree growth; Tree trials; Tropical restoration; Degraded lands; *Pinus caribaea* Morelet var *hondurensis*; *Gmelina*; *Terminalia amazonia*; *Vochysia ferruginea*; *Vochysia guatemalensis*; *Hieronyma alchorneoides*; *Calophyllum brasiliense*; *Schizolobium parabyba*; Costa Rica

1. Introduction

Selection of native tree species for establishment of commercial plantations is a continuing challenge and opportunity in tropical silviculture. Lack of information about native tree silvicultural requirements and ecological amplitudes greatly limits expanded use of native species (Butterfield and Fisher, 1992; Arias and Sánchez, 1995; Hartshorn, 1989; Lamprecht, 1990). Because of this more than 85% of the industrial forest plantations in the tropics have been established with just three genera: *Pinus, Eucalyptus and Tectona* (Evans, 1992). As of 1999, there were an estimated 8 to 11.1 million hectares of reforested land in Latin America, the majority planted with fast-growing, non-native *Pinus* and *Eucalyptus* species for timber extraction (Keipi, 1999). Hence tropical foresters have a continuing need to explore, evaluate and domesticate native tree species for reforestation, especially on degraded lands, where not

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all introduced species perform well and yet there is urgent need to restore productivity and ecosystem services. In response to this need, several research projects in the Northern region of Costa Rica have quantified native tree species' adaptability, growth in pure and mixed plantations, above ground biomass, carbon sequestration, effect of seed source, silvicultural management, tree propagation-survival-pests-diseases, impact of native trees on soil fertility, accumulation of biomass and nutrients (e.g. Butterfield, 1995a, b; Butterfield and Fisher, 1992; Delgado et al., 2003; Gonzalez, 1991; González and Fisher, 1994; Fisher, 1995; Haggar et al., 1997; Hartshorn, 1989; Montagnini et al., 1995; Montagnini and Sancho, 1990; Petit and Montagnini, 2006; Redondo and Montagnini, 2006; Piotto et al., 2003). Given the favorable results obtained in the Northern region and the rapid adoption of native tree species for reforestation projects in Costa Rica, in 1992 the Organization for Tropical Studies and other associated research institutions, initiated a program of research and outreach on native tree species on the Southern Pacific region of Costa Rica, in an effort to test the adaptation and growth of species that showed potential for reforestation of abandoned pastures on low fertility acid soils. In this paper we present an evaluation of growth at seven years of age for four native species and two introduced species planted in monospecific stands in four eco-regions along the Southern region of Costa Rica.

2. Methodology

2.1. Study site

Experimental plots with tree plantations of introduced and native species were established between June and September 1994 in the Southern region of Costa Rica in four ecological regions (Fig. 1 and Table 1). Priority in site selection was given to farms located within the mosaic of abandoned pasture lands within the Rio Terraba Watershed (Eco-regions 1, 2 and 3). In this study an eco-region combined soil (USDA soil taxonomic classification, Pérez et al., 1978; Vázques, 1979) and climate (Holdridge Life Zones – Bolaños and Watson, 1993; Tosi, 1969) as factors that hypothetically define four environments for growth. Eco-regions 1 and 2 represent the most challenging environmental conditions with their ustic soil moisture regimes and lengthy dry season each year; soils of very low fertility, very acid, clayey texture, compacted, and after the last few decades of land use, a loss of aggregation (Krishnaswamy and Richter, 2002). Eco-region 3 is dominated by volcanic soils, Andisols with loamy texture and medium to high fertility. Because these sites are at higher elevation, the dry season exerts much less water stress on plants. Eco-region 4 has only one experimental plot which is located on a young alluvial

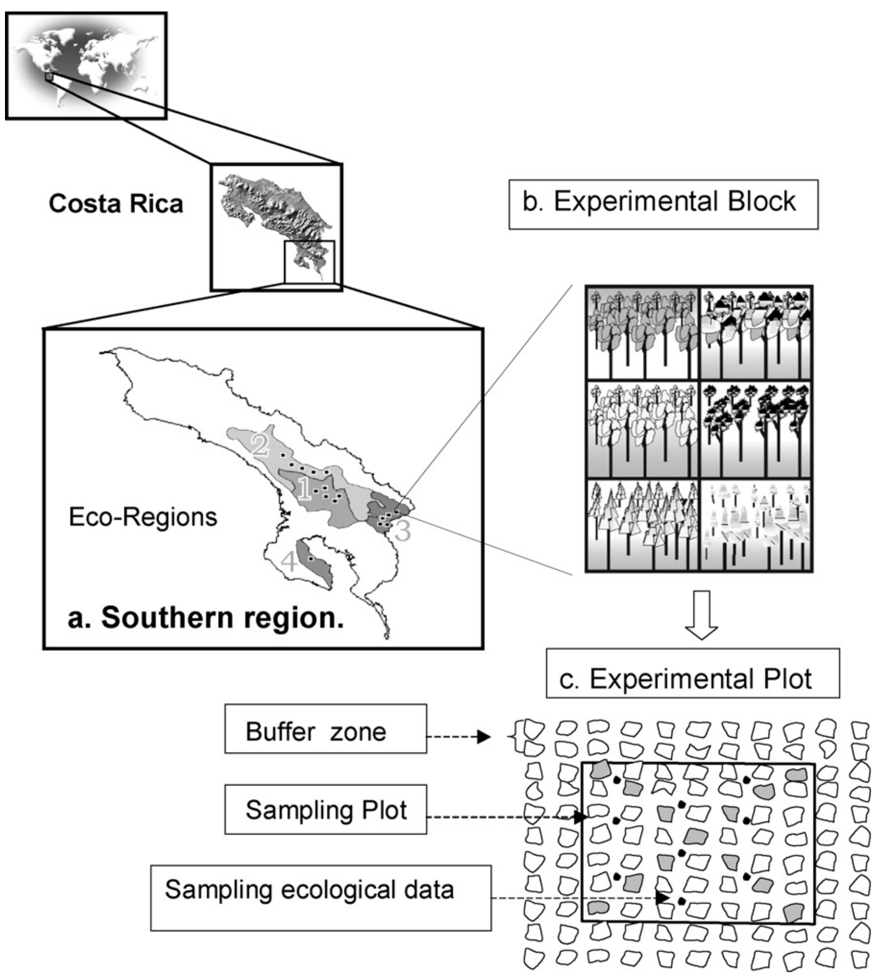

Fig. 1. Detail of experimental design and regional distribution of experimental blocks.

Table 1
Summary of the principal characteristics of selected eco-regions

Characteristics		Eco-regions			
		1	2	3	4
Holdridge life zones		Tropical moist forest	Tropical wet forest	Premontane rain forest	Tropical wet forest
Elevation range (m.a.s.l.)		700–750	450–600	800–1000	20
Dry season period in months		>3	<3	<2	0
Mean annual temperature (C°)		22.5	23.7	21.3	27
Mean annual rainfall (mm)		2688.4	3268.2	4028.4	4314
Soil sub-group		Typic Haplustepts, Haplustults	Ustic Haplohumults, Typic Haplustults	Typic Hapludand	Fluventic Eutropepts
Soil pH range (in H_2O)	0–15 cm	5.32[a] (0.04)[b]	5.12 (0.07)	5.72 (0.15)	6.31
	15–30 cm	5.36(0.07)	5.39(0.19)	5.73(0.13)	6.31
	30–45 cm	5.43(0.08)	5.39(0.07)	5.75(0.12)	6.4
Soil cation exchange capacity (cmol/kg)	0–15 cm	3.74 (0.2)	3.52 (2.2)	6.59 (1.9)	37.3
	15–30 cm	2.07 (0.3)	2.68 (2.8)	4.11 (0.9)	38.7
	30–45 cm	1.78(0.51)	2.47(3.26)	2.91(0.90)	34.6
Soil acidity Sat. %.	0–15 cm	26.7 (4.2)	64.3 (16.2)	4.1 (2.3)	0.3
	15–30 cm	69.8 (6.01)	72.7 (11.7)	5.8 (5.1)	0.9
	30–45 cm	83.5(4.79)	61.5 (27)	5.61(3.8)	1.4
Soil bulk density	0–15 cm	1.01 (0.06)	0.92 (0.2)	0.71 (0.07)	1.04
	15–30 cm	1.00(012)	1.04(0.12)	0.71(0.12)	0.93
	30–45 cm	0.98(0.09)	1.00 (0.14)	0.74 (0.18)	0.95
% Clay content	0–15 cm	45.2(6.9)	45.8(5.4)	10.5(6.9)	61.7
	15–30 cm	54.7(10.4)	52.5(10.3)	15.3(10.5)	38.4
	30–45 cm	37.4(11.5)	57.5(11.7)	10.7(11.9)	49.1
Main communities		Sábalo, Potrero Grande, Vueltas	San Isidro, Buenos Aires	San Vito, Sabalito de Coto Brus	Cañaza, Puerto Jiménez
Dominant land use		Pasture.	Pasture, pine apple, coffee and sugar cane plantations	Pasture and coffee plantations	Pasture and rice

[a] Average.
[b] Standard deviation.

Inceptisol, with loamy texture, high fertility and perudic moisture regime. Table 1 summarizes important biophysical and socioeconomic characteristics of the four eco-regions.

2.2. Selection of tree species

A broad floristic spectrum of more than 40 species native to the region was considered in choosing the species to include in this study. Species selection was based on elimination trials of 41 species, farmer preference, potential economic value, seedling availability and previous forestry trials results (Arias and Calvo-Alvarado, 2003; Calvo-Alvarado et al., 1997a, b). Eight species were included in the initial trials: *Pinus caribaea* Morelet var *hondurensis* (Barret y Golfari) *and Gmelina arborea* Roxb as the best exotic species and *Terminalia amazonia* (J. F. Gmelin) Exell, *Vochysia ferruginea* Mart., *Vochysia guatemalensis* Donn. Sm., *Hieronyma alchorneoides* Fr. Allemao, *Calophyllum brasiliense* Cambess and *Schizolobium parabyba* (Vell) Blake, as the best potential native species for reforestation.

The seed used to reproduce the seedlings was collected from at least 30 seed trees distributed along Eco-regions 1, 2 and 3, with at least 10 seed trees per eco-region. The *Gmelina* seedlings were provided by Ston Forestal of Costa Rica Inc. and the seed came from the seed orchard of this company. The pine seed from Honduras and was purchased to Semillas Tropicales Inc. (Siguateque, Honduras), specifically from three places of origin: Santa Cruz de Yojoa, Los Limones and Guanaja. Plants of both of these latter species benefited from genetic selection for forestry objectives. All of the species were reproduced in the experimental nursery of the project, located in Santa Marta de Buenos Aires at Finca LK, under a collaborative agreement with Ston Forestal of Costa Rica. Information about the results of seed and nursery trials as well as elimination trials can be found in other publications (Arias and Sánchez, 1995 and Arias and Síbaja, 1996; Arroyo, 1995).

2.3. Experimental design and measurements

A total of 16 experimental blocks were established using a randomized complete block design, nested within eco-regions on private farms. The size of the experimental plots was 11×11 trees planted at a spacing of 3 m × 3 m, for a total area of 900 square meters. A buffer zone was determined and consisted of two rows of trees. Therefore, the core sampling plot consisted of 49 trees planted in a 7×7 square (Fig. 1). The understory vegetation was cleared manually across the whole plot in all plots three times per year during the first three years and thereafter only once a year. The location of each treatment within the block was completely randomized. Two of the selected species (*Calophyllum brasiliense* and *Schizolobium parabyba*) suffered high rates of mortality during the initial year of the experiment and were therefore excluded from this analysis. Measurements of the principal dasometric variables for individual trees and for the stand were taken annually. A complete evaluation of crown parameters, trunk quality, biomass sampling and other ecological variables was carried out in February 2000.

Data on the physical-chemical properties of the soil were analyzed from soil samples taken at three depths: 0–15 cm, 15–30 cm y 30–45 cm. In each experimental block and for each depth, three sub-samples were taken and quartered to obtain the samples for the analysis. The corresponding analysis was done at the Soils and Water Laboratory at Duke University, North Carolina. The following information was obtained for each soil depth (generally following methods in Page, 1982): pH H_2O 1:2, pH $CaCl_2$ 1:2, pH NaF 1:50, total C and N (both in %); exchangeable Ca, Mg, Na, and K (in cmolc/kg): exchangeable acidity and Al (cmolc/kg) in KCL extraction; ECEC (cmolc/kg); clay (<2 μm), silt (<2–50 μm), and sand (>50 μm); and a Mehlich III extraction for P concentration (μg/g). Base saturation was estimated from the sum of exchangeable base cations: (Ca + Mg + K/ECEC × 100), as was the exchangeable acidity saturation: Al/ECEC × 100. Soil compaction was evaluated (bulk density) from samples taken at the three depths previously mentioned. Metallic cylinders 10 cm long and 5 cm wide were used. Three sub-samples were taken at each depth, which were then deposited in separate paper bags identified with the cylinder used and the depth sampled. The analysis was done in the laboratories of the Instituto Tecnológico de Costa Rica and the oven dry weight was obtained after drying soil to 100 °C. Bulk density (g/cm^3) was obtained by relating dry weight in grams to the volume of the cylinder in cm^3. Climate information collected includes: elevation (m.a.s.l.) measured with an altimeter, precipitation (mm) based on a map of isohyets (Escuela de Ingeniería Forestal, 2004) and Holdridge Life Zones (Bolaños and Watson, 1993).

Tree height was measured in meters using a height measuring pole while tree diameter was measured at breast height (1.3 m) with a measuring tape in cm. A multiple comparison of differences on total height between means of species were conducted using a Duncan test with a statistical significance of 0.05 probability level. This statistical analysis did not include Eco-region 4 because it consisted of only one experimental block. Since our aim was to test the species with the potential for fast growth and early timber production, we compared dominant tree heights in this study, estimated by averaging the three tallest trees per plot.

To study the stability of the tested species to grow consistently over a variety of sites we calculated average annual volume increment for each species at each site to graphically display yield versus species stability using the Shukla's stability variance (Butterfield, 1995a; Lin et al., 1986). In this case tree bole volume of the species was calculated with the following equations:

Gmelina arborea	$v = 0.0112 + 0.4352\,(d^2h)$	(Arias, 2002)
Pinus caribaea	$v = 0.0000638\,(d^{1.844}h^{1.007})$	(Salazar, 1976)
Vochysia guatemalensis	$v = 0.0044 + 0.468\,(d^2h)$	(Arias, 2002)
Vochysia ferruginea	$v = 0.0026 + 0.4995\,(d^2h)$	(Arias, 2002)
Terminalia amazonia	$v = 0.001 + 0.586\,(d^2h)$	(Arias, 2002)
Hieronyma alchorneoides	$v = 0.0021 + 0.5374\,(d^2h)$	(Arias, 2002)

where d = tree diameter in cm, and h = total tree height in m.

3. Results and discussion

As we indicated two species (*Calophyllum brasiliense* and *Schizolobium parabyba*) had more than 80% of mortality in all plots in Eco-regions 1, 2 and 3, during the first year of plantation establishment. The high mortality rates of *Calophyllum brasiliense* can be explained by the dominance of a well define and extended dry season of these eco-regions, a condition that this species cannot tolerate. *Calophyllum brasiliense* species has proved in other studies to be successful only in more humid climates such as the Northern region of Costa Rica (Butterfield, 1995b; Piotto et al., 2003) or in Eco-region 4, where there is no dry season and rainfall is evenly distributed throughout the year. As discussed by Carpenter et al., 2004, *Calophyllum brasiliense* had been reported to poorly tolerate full sunlight exposure and hence it appears to be better adapted to partial shade than open conditions. *Schizolobium parabyba* showed good survival and excellent growth rates during the first year of plantation establishment, but after that trees die without any apparent reason but lack of adaptation to plantation conditions. As noticed in the field, natural regeneration of *Schizolobium parabyba* grows in excellent manner and form usually as isolated or small groups of trees. The species *Hieronyma alchorneoides* showed to be particularly sensitive to the prolonged dry season of Eco-region 1, where this species suffered mortality rates between 25% to 30% in all five experimental plots. In the other three eco-regions the mortality rate of *Hieronyma alchorneoides* was less than 10%. All the other species had less than 10% of mortality in all plots and eco-regions; which in considered to be an acceptable mortality rate for commercial forestry plantations. The only exception was *Pinus caribaea* in Eco-region 4 where

Table 2
Results of the analysis of variance for the variable mean height of the stand (m), seven years after the establishment of the plantations

Source of variation	Degrees of freedom	Sum of squares[a]	Mean square	F	Prob > F
Eco-regions	2	8.53	4.26	0.16[b]	0.85
Blocks (eco-regions)	10	262.54	26.25	6.56	0.0001
Species	5	113.18	22.64	5.66	0.0007
Species x eco-regions	10	64.19	6.40	1.60	0.02
Error	33	132.01	4.00		
Total	60	580.45			

Southern region of Costa Rica.
R^2 = 0.83; C.V. = 18% mean square of the error = 1.93 average for the experiment = 10.76 m.
[a] Type III of SAS-Software recommended for unbalanced designs.
[b] The significance of the eco-regions was tested with block error (eco-regions) according to McIntosh (1983).

Table 3
Results of the Duncan multiple comparison test in each eco-region for the variable mean height of the stand (m)

Variable: mean height (m)	Eco-regions					
Species	1	Duncan	2	Duncan	3	Duncan
Gmelina arborea	10.59 ± 3.70[a]	A[b]	12.6 ± 3.97	A	12.17 ± 4.21	A
Pinus caribaea	8.57 ± 2.55	B	8.44 ± 2.08	B	10.43 ± 0.97	AB
Vochysia guatemalensis	4.86 ± 1.36	C	8.73 ± 2.94	B	9.46 ± 3.42	AB
Vochysia ferruginea	4.36 ± 1.09	C	7.99 ± 2.43	B	8.68 ± 0.88	B
Terminalia amazonia	3.30 ± 0.72	C	7.36 ± 3.32	B	10.19 ± 4.17	AB
Hieronyma alchorneoides	3.46 ± 0.69	C	6.60 ± 2.57	B	10.72 ± 1.15	AB

[a] Average ± standard deviation.
[b] Same letters within an eco-region indicate that there are no significant differences at $\alpha = 0.05$.

the mortality rate increased to about 15% probably because of the excessive humid climate of this site.

Table 2 presents the results of the ANOVA for the variable mean stand height. The interaction *Species x eco-region* was significant ($p = 0.02$). Because of this significant interaction, the multiple comparisons among species for each eco-region is presented in Table 3. Fig. 2 depicts mean tree height development of the species in each of the studied eco-regions. These results indicate that seven years after plantation establishment the differences in growth between introduced species and native species are pronounced under the environmental conditions of Eco-regions 1 and 2. These results indicate that the introduced species (*Gmelina arborea* and *Pinus caribaea*) have better adaptability and initial growth rates than the native species on acid degraded soils with an ustic soil moisture regime. As the combination of environmental factors changes, there is a positive shift towards eco-regions with better soil nutrient and water supply (Eco-regions 3 and 4), where the differences in mean stand height between introduced and native species are much less.

Based on these results, species can be grouped according to their growth potential (Table 3). Under the environmental conditions of Eco-region 1, the species fall into three groups. Through seven years of growth, *Gmelina arborea* has the greatest growth potential of all species on acid soils and ustic soil regime. *Pinus caribaea* performs second best, and the third

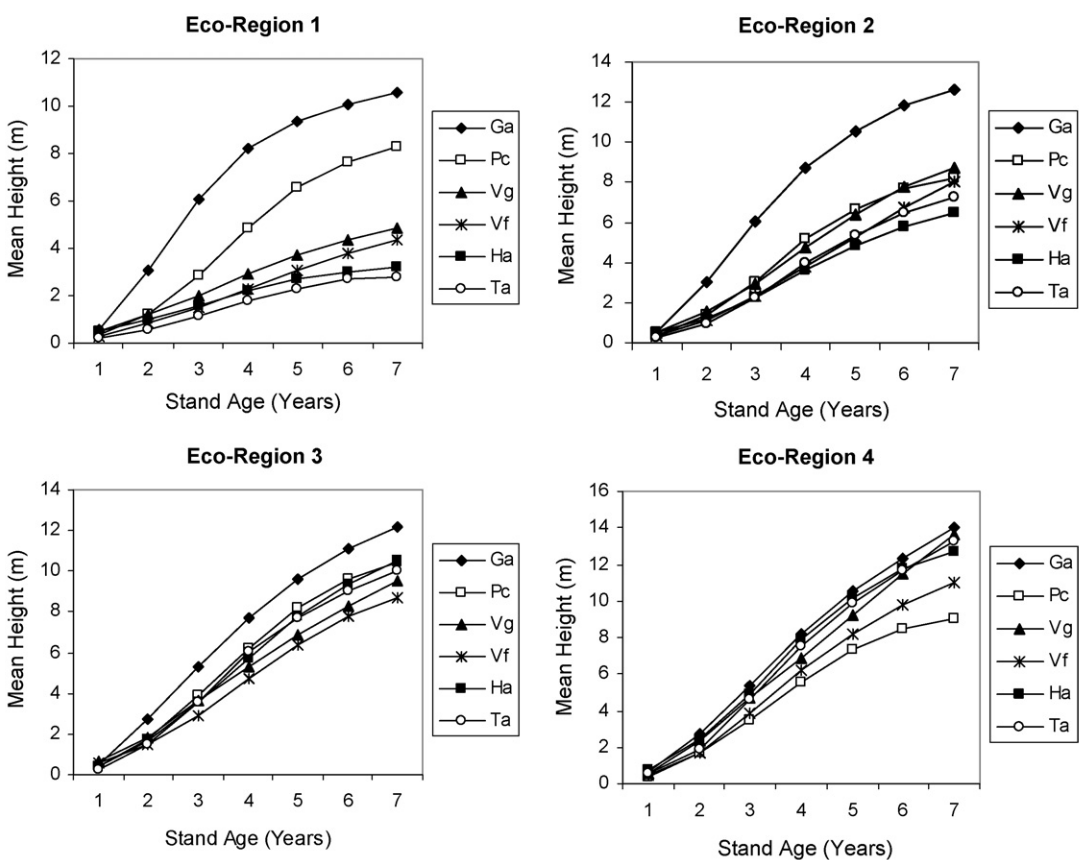

Fig. 2. Development of the mean height of the stand for the studied species by eco-region (Ga = *Gmelina arborea*, Ha = *Hieronyma alchorneoides*, Pc = *Pinus caribaea*, Ta = *Terminalia amazonia*, Vg = *Vochysia guatemalensis*, Vf = *Vochysia ferruginea*).

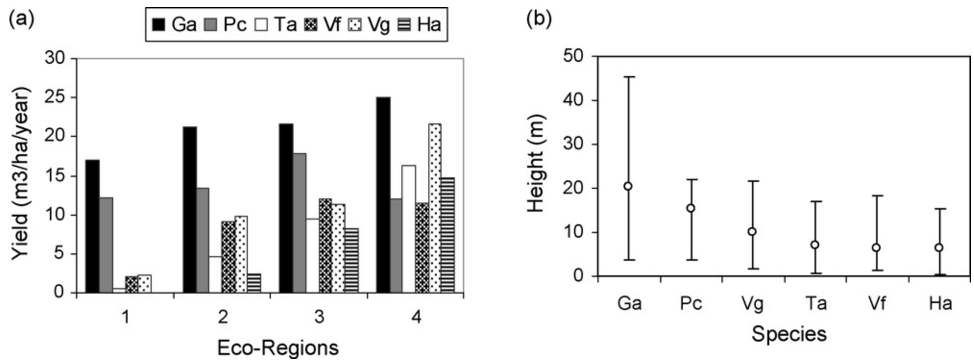

Fig. 3. (a) Mean annual volume increment (yield) by species and by eco-region at seven years of age. (b) Mean stand with maximum and minimum range by species for all plots in the Southern region of Costa Rica. (Ga = *Gmelina arborea*, Ha = *Hieronyma alchorneoides*, Pc = *Pinus caribaea*, Ta = *Terminalia amazonia*, Vg = *Vochysia guatemalensis*, Vf = *Vochysia ferruginea*).

group is composed of the native species. The native species with the most rapid growth in this region (*Vochysia guatemalensis*) attains only 46% of the mean height reached by *Gmelina arborea* and 60% of the mean height attained by *Pinus caribaea*. In Eco-region 2, the species fall into two groups. Here, *Gmelina arborea* continues to show the greatest growth potential and the second group, composed of the native species and *Pinus caribaea*. In Eco-region 3, where annual precipitation much higher (>4000 mm per year), the dry season shorter, and temperatures more moderate due to higher elevation, native species had almost the same growth potential as the introduced species. In this eco-region, the species fall into 3 groups although tree heights were much more comparable than in other eco-regions. In Eco-region 3, *Gmelina arborea* outgrew *V. ferruginia* and all other species, *Pinus caribaea, V. guatemalensis, Terminalia amazonia and Hieronyma alchornoides were in between*, neither significantly less than *G. arborea* or significantly greater than *V. ferruginia* (Table 3). In the one plot of Eco-region 4, with perudic climate and no dry season, all species except *Pinus caribaea* had comparable tree height growth (Fig. 2).

Overall, the height growth curves (Fig. 2) are polymorphic both among species and across eco-regions. The largest variation among species is in eco-region I where the height growth of some species, including *Gmelina arborea* is clearly reaching an asymptote after 7 years. There appears to be much less variation among species height growth curves in the other eco-regions. *Hieronyma alchornoides* and *Terminalia amazonia* appear to be the most responsive to eco-region, with clearly poor performance in Eco-region 1 and almost equal performance to *Gmelina arborea* in Eco-regions 3 and 4.

The analysis of species yield across eco-regions provides interesting results for the use of these species in reforestation and for site selection. Fig. 3a summarizes total volume production at seven years after the establishment of the plantations. Overall, yields are highly responsive and promoted by sites with higher nutrient and water supply environments (Table 1). The ecological optimum for the majority of the species studied can be represented by the environmental conditions of Eco-regions 3 and 4. Under conditions presented by acid soils, prolonged dry season and ustic soil moisture regime of Eco-regions 1 and 2, the combination of environmental factors restricts the yield of all of the studied native species but the introduced species. Average volume yields of *Gmelina arborea* appears to be least responsive to eco-region, at least at the end of seven years.

Fig. 3b presents the average yield (annual volume increment) of the species in the four eco-regions. The mean yield is one of the most important variables in decision-making in forestry management and expresses the potential for biomass production of the studied species. According to Fig. 3b, *Gmelina arborea* shows the greatest potential in total volume production, up to 45 m^3/ha/year within Eco-region 3. On average, *Gmelina arborea* reaches values of 20 m^3/ha/year, which equates twice as much yield as the studied native species. However, *Gmelina* also shows the greatest differences between maximum and minimum yield, which indicates that this species has a strong local-site interaction, that is, the species grows very well or very badly depending on local-site conditions, an observation very interesting, given that *Gmelina arborea* is much less responsive to eco-region than the other species (Fig. 3). Even with this undesirable characteristic, in the worse sites, *Gmelina arborea* continues to be the highest yielding species. These observations can also be seen in Fig. 4, which shows that the highest yielding species, *Gmelina arborea*, is the

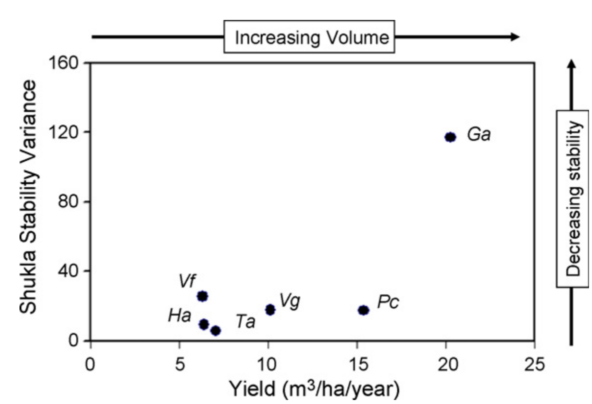

Fig. 4. Shukla's stability variante vs. average yield for 6 species. Southern region of Costa Rica. (Ga = *Gmelina arborea*, Ha = *Hieronyma alchorneoides*, Pc = *Pinus caribaea*, Ta = *Terminalia amazonia*, Vg = *Vochysia guatemalensis*, Vf = *Vochysia ferruginea*).

most unstable as expressed by high Shukla's stability variance value. The second and third highest yielding species were *Pinus caribaea* and *Vochysia guatemalensis* which were more stable than *Gmelina*. The other species are relatively stable but very much lower yielding. Similar results for Shukla's stability variance were reported for the Northern region of Costa Rica in a screening trial of 3 years of age by Butterfield (1995a). Although the experimental design and stand age of this trial is not comparable with our study, its results reinforce the conclusion that natives species are more stable but lower yielding than *G. arborea*.

The results of this study on Eco-regions 1 and 2, contrasts with findings obtained in a comparable study (on age and design) in the Northern Caribbean slope region of Costa Rica, also on acid Ultisols (Typic Tropohumult), where both *Vochysias* out-competed the best introduced species *Gmelina arborea* and *Pinus tecunumanii* (Haggar et al., 1997). A likely explanation for these differences can be associated by the presence of a well defined dry season in the Eco-regions 1 and 2 and the near absence of seasonality in the climates of these Northern regions. These climatic differences in growth and adaptability may also be associated with high soil acidity and potential Al, Fe and Mn toxicity, which can be exacerbated under poor drained, wet soils, a common condition in the Northern region. Under low soil pH, high soil acidity and prolonged saturated soil conditions, Al, Fe and Mn are more soluble increasing the toxicity effect (Buol et al., 1980; Sánchez, 1976). In the Northern region of Costa Rica, we hypothesize that introduced species *G. arboreaa* and *P. caribaea* are more sensitive to soil acidity problems due to the prevailing rainy climate than in the Southern region of Costa Rica, where the presence of a dry season lessen the nutritional limitation associated with acid soils, allowing the introduced species to display better potential growth and performance than the native species. Seasonality may alter rooting patterns of trees as well.

Of the selected native species, both *Calophyllum brasiliense* and *Schizolobium parabyba* suffered high mortality rates after planting. The remainder of the tested species show good potential for reforestation in the region, provided that species environmental requirements are considered. *Gmelina arborea*, which has been predominantly planted in Costa Rica at elevations below 500 m.a.s.l, offers interesting possibilities for the development of forestry plantations in volcanic soils in Eco-region 3 (elevation range 800–1000 m.a.s.l), where this species has previously not been recommended for reforestation projects.

As previously discussed the species *Gmelina arborea* is a highest yield but very unstable fast growing species, as such, this species is considered as a local-site specialist. Consequently, foresters recommend maximizing its potential by generating information that could explain the variation of stand productivity versus environmental factors (Butterfield, 1995a). We intended to generate this information using our data but we failed to find an acceptable correlation structure between site variables and this species. Although *G. arborea* has the greatest yield and tree height in this study, this species had problems with tree form in ways not observed by many of the native species (González and Fisher, 1994; Piotto et al., 2003).

The yield of the introduced species *Pinus caribaea* is adversely affected by high-moisture conditions presented in Eco-region 4. According to Liegel (1991) natural stands of *Pinus caribaea* are found in climates with well defined dry seasons and annual precipitation that ranges between 1500 to 3500 mm. In addition, Liegel (1991) reported that growth and survival of this species is adversely affected by poorly drained soils. As observed in Table 1, the experimental block in Eco-region 4 is on an alluvial soil with a perudic climatic regime with no dry season. Field observations indicated that the water table in this block is frequently near the surface and because of the flat topography and the prevailing rainfall regime, the soil is saturated during long periods. Significantly, nearly all the other species tolerated these poorly drained conditions, or were greatly benefited by them (Fig. 3).

The promotion of a number of native species and *Pinus caribaea* across the Southern region, where the climate and soils are very diverse is a sound recommendation due to their high stability, low mortality rate and adaptability to degraded sites. In another similar trial in a eroded pasture in Eco-region 3 (Carpenter et al., 2004), similar conclusions were also reached after 7 year of growth evaluation of several tree species, including *Pinus tecunumanii, Vochysia guatemalensis and Terminalia amazonia*. On many sites, these species are not high yielding but they have good adaptation to degraded sites with minimal plantation maintenance, a common management scenario for farmers that plant on marginal lands (Butterfield, 1995a; Haggar et al., 1998; Piotto et al., 2003). Furthermore, a study conducted in Eco-region 3 showed that native species inter-planted with nitrogen fixing trees had good growth and adaptability in eroded sites (Nichols et al., 2001).

In addition, it must be considered that native species are planted by farmers not only for timber production but for multiple uses such as fuelwood and wood for local construction. Farmers also appreciate the usefulness of native trees in agroforestry systems such as boundary lines, living fences, as shade over perennial crops such as coffee, as live barriers planted on contours to reduce soil erosion and in silvopastorial systems (Butterfield and Fisher, 1992; Cannon and Galloway, 1995; Haggar et al., 1998). Finally, the importance of reforestation with native species to promote plant biodiversity, amend soil conditions and generate a larger range of ecological services cannot be ignored. As pointed out by Lamb et al. (2005), the current scale of deforestation in tropical regions and the large areas of degraded lands underscore the urgent need for interventions to restore biodiversity, ecological functioning, and the supply of goods and ecological services, previously useful to rural communities. Several studies during the last decade have demonstrated that pure or mixed forest plantations, especially with native species, can speed forest succession by improving the environmental microsite conditions and providing habitat for seed dispersers (Carnevale and Montagnini, 2002; Cusack and Montagnini, 2004; Fisher, 1995; Haggar et al., 1997; Guariguata et al., 1995; Lugo, 1997;

Parrotta et al., 1997; Powers et al., 1997; Richter and Markewitz, 2001). Most of the Southern region of Costa Rica is a mosaic of land uses that include fragments of cut-over forest, riparian forest, productive agricultural lands as well as degraded and abandoned pasture land. Within this landscape, providing silvicultural and site-based information for a diverse list of tree species (native and introduced) is of a paramount ecological importance in order to support many on-going conservation efforts such as buffer zone management, establishment of biological corridors, and restoration of degraded land.

4. Conclusions

The early growth potential of nearly all species studied is strongly related to the eco-regions in which seedlings are planted. As site conditions become more stressful, the gap between the growth of native species and introduced species increases significantly. Hence there is a great potential for regional forestry development in the mosaic of degraded lands in the Río Térraba watershed. Adequate site selection with the help of the proposed classification by eco-regions combined with species selection for different industrial or agro-forestry uses can offer interesting options for land restoration and management.

The results presented here should be carefully interpreted considering that the species studied have different growth patterns, different adaptation strategies and different ecological needs and potentials that have not yet been studied in detail. The evaluation period of this study is relatively short and more observations will be required to complete the growth curve of the species. The analysis undertaken in this study also only considers tree height and volume growth. Other important information must be considered to judge the reforestation potential of these species such as species morphology and efficient nutrient and water use, and effects on the entire ecosystem. Furthermore, for these native species the natural genetic variation is not yet known. With this information it will be possible to develop the silviculture management and sustainable forestry production of goods and services with native species.

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