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# Growth, carbon sequestration, and management of native tree plantations in humid regions of Costa Rica

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**Abstract** The Costa Rican government has provided incentives for reforestation programs since 1986 and initiated a Payment for Environmental Services program in 1996. These incentives yielded native species reforestation programs throughout the country. This research aims to provide information about growth, carbon sequestration, and management of seven native tree species (*Vochysia guatemalensis, Vochysia ferruginea, Hyeronima alchorneoides, Calophyllum brasiliense, Terminalia amazonia, Virola koschnyi*, and *Dipteryx panamensis*) growing in small and medium-sized plantations in the Caribbean and Northern lowlands of Costa Rica. A total of 179 plots were evaluated in 32 farms. Overall, I found that *V. guatemalensis, V. ferruginea, H. alchorneoides*, and *T. amazonia* were the species with the fastest diameter, total height, and volume growth; and *T. amazonia* and *D. panamensis* sequestered more carbon. Moreover, I found that the plantations that had been thinned before this assessment had the best growth. The results of the present research enhance the criteria elaborated in previous research findings to improve species choices for reforestation and silvicultural management in Costa Rica and in other regions with similar ecological features. Furthermore, they support the concept that tropical plantations can serve diverse economic, social, and ecological functions that may ultimately help reduce atmospheric $CO_2$ accumulation.

**Keywords** Productivity · Silvicultural management · Allometric equations · Environmental services · Timber production · Aboveground biomass

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## Introduction

Tropical tree plantations have been considered relatively small carbon sinks (Montagnini and Porras 1998; Shepherd and Montagnini 2001; Schroeder 1992; Losi et al. 2003). However, they may become more important as plantations are expected to increase in area over the next few decades (Schroeder 1992; Houghton 1996; FAO 2001). In Costa Rica, during the 1970s and 1980s, reforestation programs were established using a few tree species, especially exotics such as *Cupressus lusitanica* Mill., *Pinus* spp., *Gmelina arborea* L., and *Eucalyptus* spp., as well as the native species *Cordia alliodora* (Ruiz & Pav.) Oken (González and Fisher 1994). Although some planted species have high adaptability and rates of growth, some tree species failed to establish in the degraded soils of abandoned pastures (González and Fisher 1994). Subsequent research focused on tree species that could tolerate poor soil conditions.

One of the most relevant studies of growing native species on plantations in the Caribbean lowlands of Costa Rica began in the mid 1980s at La Selva Biological Station (Butterfield 1990). The findings of these trials showed that several native species not previously used for reforestation had rapid growth rates and high adaptability to degraded soils in the first phases of plantation development. This suggests that they may be good candidates for use in plantations. Those findings and the implementation of government incentives in Costa Rica such as the Payments for Environmental Services (PES) Program has increased the number of native tree plantations in the last decade, especially on small and medium-sized farms in rural areas (Ortiz and Kellenberg 2002). One of the environmental services recognized by the PES program is carbon sequestration (Subak 2000). Carbon sequestration projects that promote agroforestry, small-scale plantations, and natural forest regeneration and preservation such as the PES in Costa Rica are expected to improve the livelihoods of small-scale farmers, communities, and indigenous peoples (CIFOR 2002). Thus, studies of carbon sequestration within systems such as tree plantations are needed in order to assess the effectiveness of those ecosystems in providing revenues to landowners and society.

In this paper I report on the evaluation of seven native tree species growing in small and medium-sized plantations in the Caribbean and Northern lowlands of Costa Rica. The main objective of this study is to provide information about the growth and management of the seven species for timber production and carbon sequestration. This information contributes to the development of better criteria for species selection for reforestation programs in regions with similar ecological conditions, especially because most of the tree species included in this study have a large natural range of distribution in Latin America. Moreover, information about long-term performance of native tree species is necessary to guarantee better results and diminish the investment risk for the rural farmers (Piotto et al. 2003a; Lamb et al. 2005).

## Materials and methods

### Research sites

The research was conducted in pure plantations located in Sarapiqui and San Carlos counties in Costa Rica. Both locations fulfill one of the requirements needed to use the allometric equations, which is growth in regions with conditions similar to the site where the equations were developed (Montero and Montagnini 2005). All plantations were planted at similar initial density from 1,000 to 1,100 trees per hectare. These plantations were established in degraded soils after abandonment from pasture for cattle and agriculture land uses. Local farmers provided the manual labor to establish the plantations and fertilizers were applied only once. Most of these plantations were established with government incentives (Delgado 2002; Piotto et al. 2003a).

### *Sarapiqui*

The study site is located in the Caribbean lowlands of Costa Rica. Mean annual precipitation is 3,500–5,000 mm, and the mean annual temperature is 24°C. Elevation ranges from 30 to 200 masl with flat to undulating terrain. In general, soils belong to the Ultisol and Inceptisol orders and have slow or impeded drainage and very low to medium fertility (Costa Rica 1979; Piotto et al. 2003a).

Thirteen farms were evaluated and 62 plots were measured. Most farms had more than one single-species plantations. These plantations were established between 1990 and 1995 with the association of local farmers: the County Agricultural Center of Sarapiqui (CACSA) and a non-governmental organization (NGO) called the Foundation for the Development of the Central Volcanic Range (FUNDECOR).

### *San Carlos*

This study site is located in Costa Rica's North Huetar Region. Mean annual precipitation is 2,000–4,000 mm, with a mean annual temperature of 25°C. The overall topography is flat to undulating terrain and the elevation varies between 100 and 400 masl. In general, soils belong to the Ultisol and Inceptisol orders. The principal soil limitations are low pH, low to medium fertility, and poor drainage (Delgado 2002).

Nineteen farms were evaluated and 117 plots were measured. Most of the farms had more than one single-species plantations that were established between 1990 and 1995 as part of a project on native species sponsored by the Technological Institute of Costa Rica (ITCR) and the NGO called COSEFORMA (Cooperation in the Timber and Wood Sectors Project) (Delgado 2002).

## Species under study

This research analyzed seven native tree species (local names are in parentheses): *Vochysia ferruginea* Mart. (botarrama), *V. guatemalensis* Donn. Sm. (chancho), *Hyeronima alchorneoides* Fr. Allemao (pilon), *Calophyllum brasiliense* Cambess (cedro maria), *Terminalia amazonia* (J.F. Gmel.) Exell (roble coral), *Virola koschnyi* Warb (fruta dorada), and *Dipterix panamensis* (Pittier) Record & Mell (almendro) (Table 1). These seven species were chosen because they were the most frequently planted by farmers at both locations. In addition, the PES program is available for reforestation programs using these species. However, only six species were evaluated at San Carlos since plantations from 9 to 14 years old of *C. brasiliense* were not found.

## Methods

### *Collection of field measurements*

At every plot, I measured the diameter at breast height (DBH) for each species of concern at a height of 1.30 m from the ground. In addition, I measured the total height of between

**Table 1** Characteristics of native tree species grown in the Caribbean and North lowlands of Costa Rica

| Species name | Common name | Family | Native range | Growth, habitat |
|---|---|---|---|---|
| *Vochysia guatemalensis* Donn. Sm | Chancho, Mayo | Vochysiacea | Mexico to Panama | Upper canopy, early mid-successional. Fast growth |
| *Calophyllum brasiliense* Cambess | Cedro maria | Clusiaceae | Mexico to South America and the Antilles | Canopy tree. Moderately shade-tolerant. Slower growth |
| *Terminalia amazonia* (J.F.Gmel.) Exell | Amarillon, Roble Coral | Combretaceae | Mexico to South America and the Antilles | Canopy tree. Heliophyte. Moderately fast growth. |
| *Virola koschnyi* Warb | Fruta Dorada | Myristicaceae | Belize to Panama and Ecuador | Canopy tree, mid-successional. Slower growth |
| *Dipteryx panamensis* (Pittier) Record and Mell | Almendro | Fabaceae-Papilionoideae | Nicaragua to Colombia | Canopy tree, late successional. Slower growth |
| *Hyeronima alchorneoides* Fr. Allemao | Pilon | Euphorbiaceae | Belize to the Amazon | Canopy tree. Early–mid-successional. Moderately fast growth |
| *Vochysia ferruginea* Mart | Botarrama | Vochysiaceae | Nicaragua to Peru and Brazil | Heliophyte tree, durable, rapid growth. Found in secondary forests. |

Source: Jiménez-Madrigal et al. (2002)

six and eight trees per plot to calculate the height of the remaining trees within the plots using logarithmic equations (See Appendix 1). The selected trees for measuring were based on tree size and location within the plots. I chose at least two individuals representing each of three size classes in the plot. The size classes were defined based on the position of the trees in each stand as dominant, co-dominant, and suppressed trees.

The number of plantations per species, plot size, and number of measured plots varied from site to site due to differences in plantation size and shape, availability of plantations in both regions, and the criterion to evaluate a minimum of 5% of the total planted area at each farm. The plot areas were between 225 to 784 $m^2$. These plantations varied in size from 0.1 to a maximum of 5 ha (Delgado 2002; Piotto et al. 2003a).

## *Data analysis*

Average DBH, total height, basal area, volume, aboveground biomass, and carbon sequestration were calculated for each plot, and at the tree level for each species. The volume of individual trees was estimated following Newbould (1967): volume = basal area × estimated total height × 0.5.

I estimated aboveground biomass for the seven species using measurements of DBH and measured and estimated total heights based on the equations developed by Montero and Montagnini (2005) in Costa Rica (See Appendix 2). Specific equations were employed for each species and each tree component (total tree, stem, branches, and foliage separately). A correction factor (See Appendix 2) was used to counteract the systematic bias introduced into calculations when log transformations were utilized (Sprugel 1983). Based on the assumptions in similar studies I estimated carbon to equal 50% of a tree's biomass

(Brown and Lugo 1982; Schroeder 1992; Montagnini and Porras 1998; Roy et al. 2001; Malhi et al. 2004). The data for this research was stratified in age classes 9–10, 11–12, and 13–14 years in order to more accurately represent the specific situation for each location and species.

To calculate the basal area, volume, and aboveground biomass per hectare, I used two steps. First, for each plot, I estimated the stand density per ha by multiplying the number of individuals in the plot by 10,000 $m^2$ divided by the plot area. Second, I multiplied the obtained stand density by the values per plot for each variable.

One-way analyses of variance (ANOVA) for different sample sizes were used to determine the statistical significance for differences in carbon sequestration and growth rates between species within each location (Sarapiqui and San Carlos). In addition, Tukey's pair-wise comparisons were used to determine statistically significant differences within each variable that was analyzed. Regression analyses were performed to evaluate relationships between carbon sequestration, diameter, total height and growth parameters with density, species, plantation age, and location. For all analyses interactions were tested and residual plots were analyzed to ensure that the model assumptions were satisfied. Analyses were performed with SAS System Release 8.2 (2001), and statistical significance was fixed at $P < 0.05$.

## Results

### Growth of the native tree plantations

Overall, the Sarapiqui plantations had higher values than the San Carlos plantations for DBH, total height, basal area, and tree volume (Table 2). The density of trees varied among locations and species, with *D. panamensis* being the species found in the highest density in both study sites. Stand density for this species varied from 500 to 1,067 individuals per ha. *V. guatemalensis* (11–12 years), ranging from 226 to 557 individuals and *V. ferruginea* (11–12 years) (202–375 individuals) had the lowest stand density in Sarapiqui, while *V. ferruginea* (9–10 years) (329–680 individuals) and *T. amazonia* (9–10 years) (400–440 individuals) the lowest density in San Carlos (Table 2).

Plantation age did not significantly predict stand density ($r^2 = 0.71$, $P = 0.8817$), but location (Sarapiqui and San Carlos) and species did ($r^2 = 0.71$, $P < 0.0001$). Silvicultural management differed between locations according to the goals of the organizations that supported the reforestation projects, availability of resources, and stakeholders' reforestation goals. In San Carlos the plantations were established by a former NGO called COSEFORMA, and at present, studies on those plantations have been carried out by the ITCR (Delgado 2002). Although management recommendations were made to landowners, sometimes implementation was constrained by a lack of funding or a lack of interest (Castillo M, personal communication, August 5, 2004). Delgado (2002) mentioned that after nearly a decade only 57% of the landowners had executed a thinning due to lack of funding and technical support. Moreover, 15% of the plantations were not being managed because the farmers were using them for restoration or environmental services purposes (Delgado 2002). However, I observed that some plantations had been managed (i.e., more than one thinning), and some landowners were already selling the products of their thinning, especially of the fast-growing species *V. guatemalensis* and *V. ferruginea*, and in a few cases *H. alchorneoides*.

**Table 2** Principal statistics for seven native tree species in pure plantations in Costa Rica

| Location/ species | Age (Years) | *N* (plots) | Density (number of trees/ha) | Diameter (cm) | Total height (m) | Basal area ($m^2$/ha) | Volume ($m^3$/ha) |
|---|---|---|---|---|---|---|---|
| Sarapiqui | | | | | | | |
| *D. panamensis* | 9–10 | 1 | 712[a] | 17.5[b] | 17.4[a] | 17.9[a,b] | 162.0[a] |
| *D. panamensis* | 11–12 | 4 | 692 (194)[a,b] | 12.9 (0.9)[b] | 15.5 (1.4)[a] | 9.5 (2.1)[b] | 77.4 (17.5)[a] |
| *T. amazonia* | 9–10 | 7 | 576 (58)[a,b,c] | 21.6 (0.7)[b] | 20.2 (1.0)[a] | 22.4 (0.4)[a,b] | 236.9 (11.8)[a] |
| *T. amazonia* | 11–12 | 10 | 385 (105)[b,c] | 22.4 (3.5)[a,b] | 20.4 (2.8)[a] | 15.4 (3.6)[a,b] | 164.6 (50.9)[a] |
| *H. alchorneoides* | 9–10 | 4 | 563 (66)[a,b,c] | 21.3 (3.3)[b] | 18.6 (2.8)[a] | 20.6 (5.9)[a,b] | 199.5 (81.2)[a] |
| *H. alchorneoides* | 11–12 | 9 | 338 (72)[c] | 21.8 (5.3)[a,b] | 21.1 (3.2)[a] | 13.1 (5.4)[a,b] | 148.0 (70.7)[a] |
| *V. guatemalensis* | 9–10 | 5 | 545 (81)[a,b,c] | 25.0 (10.2)[a,b] | 18.5 (3.2)[a] | 30.0 (19.9)[a] | 309.6 (239.1)[a] |
| *V. guatemalensis* | 11–12 | 4 | 269 (77)[c] | 34.1 (1.5)[a] | 21.6 (1.1)[a] | 25.3 (8.2)[a,b] | 278.7 (96.0)[a] |
| *V. ferruginea* | 9–10 | 2 | 353 (81)[c] | 24.0 (2.2)[a,b] | 16.5 (1.2)[a] | 17.7 (6.6)[a,b] | 155.8 (60.0)[a] |
| *V. ferruginea* | 11–12 | 4 | 280 (60)[c] | 34.0 (2.6)[a] | 21.9 (2.2)[a] | 25.6 (2.8)[a,b] | 285.3 (45.0)[a] |
| *V. koschnyi* | 11–12 | 8 | 436 (106)[a,b,c] | 22.5 (4.1)[a,b] | 18.2 (3.8)[a] | 18.2 (5.8)[a,b] | 178.2 (80.2)[a] |
| *C. brasiliense* | 11–12 | 7 | 684 (224)[a,b] | 19.3 (3.7)[b] | 15.9 (1.1)[a] | 19.0 (3.0)[a,b] | 154.4 (27.6)[a] |
| San Carlos | | | | | | | |
| *D. panamensis* | 9–10 | 6 | 688 (184)[a,b,c] | 12.7 (1.3)[d] | 14.4 (2.4)[a] | 9.2 (2.7)[d] | 70.8 (26.4)[c] |
| *D. panamensis* | 13–14 | 19 | 852 (154)[a] | 12.7 (1.2)[d] | 14.7 (2.1)[a] | 11.4 (1.9)[c,d] | 90.0 (22.5)[c] |
| *T. amazonia* | 9–10 | 4 | 411 (22)[c] | 16.8 (1.1)[c,d] | 17.7 (1.7)[a] | 9.3 (1.0)[d] | 85.0 (18.1)[c] |
| *H. alchorneoides* | 9–10 | 8 | 552 (199)[a,b,c] | 16.9 (2.7)[c,d] | 17.6 (2.0)[a] | 11.8 (1.6)[c,d] | 106.2 (13.5)[c] |
| *H. alchorneoides* | 11–12 | 20 | 680 (202)[a,b,c] | 15.4 (2.6)[c,d] | 17.2 (2.5)[a] | 12.8 (0.5)[c,d] | 115.8 (44.5)[b,c] |
| *V. guatemalensis* | 9–10 | 6 | 498 (153)[a,b,c] | 25.3 (1.5)[a] | 20.6 (1.5)[a] | 25.5 (8.8)[a,b] | 269.3 (96.1)[a,b] |
| *V. guatemalensis* | 11–12 | 19 | 654 (195)[a,b,c] | 23.6 (3.8)[a,b] | 19.6 (3.6)[a] | 28.2 (7.5)[a,b] | 289.8 (124.6)[a] |
| *V. guatemalensis* | 13–14 | 4 | 711 (63)[a,b,c] | 24.0 (0.6)[a,b] | 16.3 (1.1)[a] | 32.7 (1.1)[a] | 272.4 (29.8)[a] |
| *V. ferruginea* | 9–10 | 5 | 434 (176)[b,c] | 23.7 (2.1)[a,b] | 16.8 (1.4)[a] | 19.0 (5.9)[b,c,d] | 160.0 (49.9)[a,b,c] |
| *V. ferruginea* | 11–12 | 10 | 587 (219)[a,b,c] | 20.6 (5.1)[a,b,c] | 15.4 (4.3)[a] | 18.2 (4.2)[b,c,d] | 146.6 (63.4)[a,b,c] |
| *V. koschnyi* | 9–10 | 1 | 400[c] | 19.7[a,b,c] | 16.1[a] | 13.4[c,d] | 100.4[c] |
| *V. koschnyi* | 13–14 | 16 | 817 (138)[a,b] | 17.4 (2.7)[b,c,d] | 14.7 (2.6)[a] | 20.6 (5.7)[b,c] | 165.2 (71.0)[a,b,c] |

Values are means and standards deviations (in parentheses). Means are significantly different when standard deviation are followed by different letters ($P < 0.05$) in each column and location

In Sarapiqui, the forest plantations were established by two local NGOs FUNDECOR and CACSA. Overall, those organizations had a close relationship with the landowners and the plantations were thinned one to three times. However, a few landowners were not willing to manage the plantations because they established them as a means for forest restoration and conservation (Sanchun A, personal communication May 25, 2004).

Stand density was negatively related to both DBH and total height at both locations (DBH $t = -9.93$, $P < 0.0001$; total height $t = -11.09$, $P < 0.0001$). In general, the plantations of the same species with the highest densities had the lowest values for DBH and total height. At both locations, *D. panamensis* had the lowest DBH (range from 12.0 to 19.1 cm) and total height values (range from 10.5 to 18.3 m). On the other hand, in Sarapiqui, *V. guatemalensis* (11–12 years) had the highest DBH (28.5–37.0 cm), followed by *V. ferruginea* (11–12 years) (29.0–38.2 cm). The latter also had the tallest trees on average ranging from 18.4 to 24.2 m. In San Carlos, *V. guatemalensis* (9–10 and 13–14 years) had the highest DBH (21.3–26.7 and 23.5–24.4 cm) and the former the greatest total height values (18.6–22.1 m), respectively. Those results confirm that *V. guatemalensis* is a species that grows very well along both regions and *D. panamensis* is a slow-growing species. The lack of management on *D. panamensis* stands was the main reason why this species presented the highest stand density. At both regions landowners were not managing the plantations due to its slow growth, and suppressed trees were found. For example, in two of the evaluated farms with several pure stands planted, landowners were thinning *V. ferruginea, V. guatemalensis*, and *H. alchorneoides*, whereas the *D. panamensis* plantations did not receive any management. Moreover, landowners consider *D. panamensis* stands more important for their benefits to the green great macaw (*Ara ambigua*), an endangered species that relies on this tree for nesting and feeding. At both locations, *D. panamensis* stands also had the lowest values for total volume and *V. guatemalensis* stands the highest (Table 2).

### Carbon sequestration

The data for carbon sequestration are presented in tons per ha for the tree's components (stem, branches, foliage, and total tree) and the values corresponding to individual trees are given in kilograms (Table 3). Overall, Sarapiqui plantations presented higher values of carbon sequestration than did San Carlos plantations.

In San Carlos, the species with the highest values of carbon per tree were *V. guatemalensis* (9–10 years) (range from 50.4 to 104.0 kg C) and *T. amazonia* (9–10 years) (range from 51.8 to 79.6 kg C) while that with the lowest value was *V. koschnyi* (13–14 years) (13.5–47.5 kg C). The per ha estimates for carbon sequestration indicated that *D. panamensis* (13–14 years) (20.5–55.1 Mg C) and *V. guatemalensis* (13–14 years) (38.7–47.2 Mg C) were the species that sequestered the most carbon. The species *V. koschnyi* (9–10) (11–12) had the lowest values, ranging from 13.2 to 42.2 Mg C.

In Sarapiqui, the species that had the highest values of carbon per tree were *T. amazonia* (11–12 years) (range from 83.7 to 185.9 kg C) and *H. alchorneoides* (11–12 years) (range from 58.7 to 237.5 kg C) and the lowest values were for *V. koschnyi* (11–12 years) (13.5–47.5 kg C). The estimates of the values per ha for carbon sequestration indicated that *T. amazonia* (9–10 years) (range 52.2–79.1 Mg C) had the highest values while *V. koschnyi* (11–12) (14.7–36.5 Mg C) had the lowest. The plantation location ($r^2 = 0.67$, $P = 0.0001$), species ($P < 0.0001$), and density ($P = 0.03$) were significant predictors of carbon sequestration per ha. However, the plantation age was not a good predictor ($P = 0.36$).

The percentage of carbon sequestration in the three different components (stem, branches, and foliage) was similar in both locations Sarapiqui and San Carlos. The carbon allocated in the stems varied from 50 (*V. ferruginea*) to 92% (*V. guatemalensis*). The carbon allocated in the branches varied from 4 (*V. guatemalensis*) to 43% (*H. alchorneoides*). Finally, the carbon allocated in the foliage varied from 3 (*V. guatemalensis*) to 18% (*V. ferruginea*).

## Discussion

### Growth of native tree plantations

The planting of fast-growing native tree species is relatively nascent in much of the tropics, and we know very little about the potential capabilities for increasing productivity or

**Table 3** Carbon sequestration estimations for seven native tree species in pure plantations in Costa Rica

| Location/ species | Age (Years) | *N* (plots) | Carbon storage per ha (Mg) | | | | Carbon storage per tree (Kg) |
|---|---|---|---|---|---|---|---|
| | | | Stem | Branches | Foliage | Total | |
| Sarapiqui | | | | | | | |
| *D. panamensis* | 9–10 | 1 | 60.6[a] | 23.0[a,b] | 7.5[a,b] | 91.0[a] | 128.0[a] |
| *D. panamensis* | 11–12 | 4 | 26.0 (5.7)[b,c] | 8.0 (1.9)[b,c,d] | 2.8 (0.6)[c,d] | 36.9 (0.8)[b,c,d] | 54.7 (11.8)[a] |
| *T. amazonia* | 9–10 | 7 | 58.8 (0.7)[a,b] | 15.9 (0.6)[a,b,c,d] | 4.4 (0.1)[c,d] | 79.1 (1.4)[a,b] | 138.1 (16.3)[a] |
| *T. amazonia* | 11–12 | 10 | 40.9 (11.3)[a,b,c] | 11.1 (3.4)[a,b,c,d] | 3.1 (0.9)[c,d] | 55.1 (15.6)[a,b,c] | 151.8 (53.2)[a] |
| *H. alchorneoides* | 9–10 | 4 | 36.1 (12.8)[a,b,c] | 26.9 (14.4)[a] | 3.4 (1.3)[c,d] | 66.3 (28.5)[a,b,c] | 120.0 (53.4)[a] |
| *H. alchorneoides* | 11–12 | 9 | 24.9 (11.6)[c] | 20.3 (13.6)[a,b,c] | 2.3 (1.1)[c,d] | 46.5 (26.2)[a,b,c] | 144.3 (84.8)[a] |
| *V. guatemalensis* | 9–10 | 5 | 40.5 (3.7)[a,b,c] | 2.0 (0.8)[c,d] | 1.7 (0.1)[c,d] | 44.5 (31.0)[a,b,c] | 81.4 (63.7)[a] |
| *V. guatemalensis* | 11–12 | 4 | 38.3 (11.0)[a,b,c] | 1.5 (0.4)[d] | 1.4 (0.5)[d] | 41.2 (12.6)[b,c] | 137.9 (9.7)[a] |
| *V. ferruginea* | 9–10 | 2 | 11.7 (3.7)[c] | 7.8 (3.5)[b,c,d] | 4.0 (2.3)[c,d] | 23.5 (9.4)[c] | 65.3 (11.8)[a] |
| *V. ferruginea* | 11–12 | 4 | 19.2 (1.6)[c] | 12.5 (1.3)[a,b,c,d] | 4.6 (0.6)[b,c] | 36.3 (3.5)[b,c] | 132.9 (25.4)[a] |
| *V. koschnyi* | 11–12 | 8 | 13.7 (5.0)[c] | 6.3 (3.2)[b,c,d] | 2.7 (1.3)[c,d] | 22.5 (9.4)[c] | 53.2 (25.9)[a] |
| *C. brasiliense* | 11–12 | 7 | 36.2 (5.1)[a,b,c] | 15.2 (2.7)[a,b,c,d] | 8.5 (1.6)[a] | 60.0 (8.8)[a,b,c] | 103.1 (61.5)[a] |
| San Carlos | | | | | | | |
| *D. panamensis* | 9–10 | 6 | 25.5 (8.0)[a,b,c,d] | 8.4 (2.6)[a,b,c] | 2.6 (0.9)[a,b,c] | 36.5 (11.5)[a,b] | 50.8 (12.4)[a,b] |
| *D. panamensis* | 13–14 | 19 | 31.3 (6.3)[a,b,c] | 9.7 (2.3)[a] | 3.4 (0.8)[a,b] | 44.4 (9.3)[a] | 52.8 (12.8)[a,b] |
| *T. amazonia* | 9–10 | 4 | 20.9 (3.1)[a,b,c,d] | 5.1 (0.9)[a,b,c] | 1.5 (0.2)[c] | 27.5 (4.2)[a,b,c] | 67.3 (12.7)[a,b] |
| *H. alchorneoides* | 9–10 | 8 | 17.8 (2.6)[b,c,d] | 9.0 (3.1)[a,b] | 1.5 (0.3)[b,c] | 28.3 (5.6)[a,b,c] | 59.3 (29.2)[a,b] |
| *H. alchorneoides* | 11–12 | 20 | 18.6 (6.5)[a,b,c,d] | 8.5 (5.2)[a,b,c] | 1.6 (0.6)[b,c] | 28.8 (12.2)[a,b,c] | 45.2 (23.8)[a,b] |
| *V. guatemalensis* | 9–10 | 6 | 33.2 (11.8)[a,b] | 1.8 (0.6)[c] | 1.5 (0.5)[c] | 36.6 (12.9)[a,b] | 75.1 (19.6)[a] |
| *V. guatemalensis* | 11–12 | 19 | 35.9 (13.7)[a] | 2.2 (0.5)[c] | 1.6 (0.4)[b,c] | 39.7 (14.5)[a,b] | 65.6 (27.1)[a,b] |
| *V. guatemalensis* | 13–14 | 4 | 36.1 (3.0)[a] | 2.5 (0.1)[b,c] | 1.9 (0.1)[b,c] | 40.5 (3.3)[a,b] | 56.9 (0.4)[a,b] |
| *V. ferruginea* | 9–10 | 5 | 11.4 (3.9)[d] | 7.3 (2.4)[a,b,c] | 4.2 (1.4)[a] | 23.0 (6.9)[a,b,c] | 55.6 (12.5)[a,b] |
| *V. ferruginea* | 11–12 | 10 | 11.4 (2.7)[d] | 5.5 (3.0)[a,b,c] | 2.7 (1.5)[a,b] | 20.0 (6.9)[b,c] | 40.5 (26.1)[a,b] |
| *V. koschnyi* | 9–10 | 1 | 8.4[d] | 2.7[b,c] | 1.3[c] | 12.4[c] | 30.9[b] |
| *V. koschnyi* | 13–14 | 16 | 14.1 (4.8)[c,d] | 4.9 (2.8)[a,b,c] | 2.2 (1.1)[b,c] | 21.2 (8.7)[a,b,c] | 27.0 (12.2)[b] |

Values are means and standards deviations (in parentheses). Means are significantly different when standard deviation are followed by different letters ($P < 0.05$) in each column and location

potential problems that may limit yields in the long-term (Tiarks et al. 1998; Piotto et al. 2003a; Lamb et al. 2005). The results of the present study confirm the high productivity, in terms of volume yield, of the fast-growing species *V. guatemalensis, V. ferruginea*, and *H. alchorneoides* as well as the low productivity of the slower-growing species *D. panamensis* and *C. brasiliense* (Delgado 2002; Piotto et al. 2003a, b; Petit and Montagnini 2004; Redondo-Brenes and Montagnini 2006). *V. guatemalensis, H. alchorneoides*, and *T. amazonia* are three of the species most frequently planted in small to medium-sized reforestation programs in the Caribbean, Northern, and Southern lowlands of Costa Rica (Russo 2002; Calvo and Arias 2002; Delgado 2002; Piotto et al. 2003b). As such much is known about several aspects of this species' domestication, including seed collection and germination, vegetative propagation, and preliminary stages of tree genetic improvement

(Montagnini et al. 2003). *T. amazonia* is one of the most promising species for reforestation programs because of its high-timber quality in comparison to *V. guatemalensis* (Calvo and Arias 2002; Piotto et al. 2003b; Carpenter et al. 2004). On the other hand, *C. brasiliense* and *D. panamensis* had the lowest growth rate in general, reflecting a pattern documented by previous studies in the same region (Chinchilla-Mora and Mora-Chacón 2002; Russo 2002; Piotto et al. 2003a). Their high timber value justifies their use in spite of their slow growth (Petit and Montagnini 2004). *V. ferruginea* is also preferred by farmers due to its good timber quality (Petit and Montagnini 2004).

Several authors have reported preliminary results concerning the performance of native species in the regions discussed in this study, but for younger or similar-aged plantations (Gonzalez and Fisher 1994; Butterfield 1996; Powers et al. 1997; Haggar et al. 1998; Delgado 2002; Piotto et al. 2003a, b; Petit and Montagnini 2004; Solis-Corrales and Moya-Roque 2005a, b, c). The general conclusion from all these studies highlights the need to continue monitoring these plantations in order to improve the management prescriptions for these species. Where there have been appropriate species-site matching and when management prescriptions are effective plantations usually remain healthy and productive. In addition, the productivity of plantations needs to be high and sustainable due to the significant initial investments required, especially for smallholders (Tiarks et al. 1998; Lamb et al. 2005).

## Management of native tree plantations for timber production

Stand density best explains the differences in growth between plantations of the same species in the two locations for the present study. Lower density plantations of a single species yielded higher DBH, total height, and tree volume. There are some studies of a variety of single-species populations that have shown a relationship between the maximum number of individuals that can occupy a site and the average size of the individuals (Smith et al. 1997). Other studies point to the need for managing plantations to accelerate diameter growth, shorten rotation cycles, improve wood quality, and increase yields (Piotto et al. 2003b). Kanninen et al. (2004), mention that the success in the management of plantations of fast-growing tropical tree species can be achieved only by performing intensive and timely silvicultural interventions. Furthermore, data on tree plantations' growth has shown that the failure to reduce plantation density in an opportune fashion leads to crown recession, rapid reductions in diameter growth, increases in height/diameter ratios and within a short time, even reductions in height growth, including dominant height (Galloway et al. 1996).

Overall for this study, thinning to concentrate the potential wood production of the stand on a limited number of selected trees was effective. The total yield was augmented largely by harvesting trees that would ultimately die from competition with other trees. The outcomes after a thinning treatment for the species part of this study were highlighted by Piotto et al. (2003b) and Jacobs et al. (2005). Piotto et al. (2003b) found that 1 year after a third thinning, *C. brasiliense* stands without thinning were almost 4 cm shorter than individuals in the plantations that were thinned the previous year. *V. guatemalensis* stands differed by more than 3 cm, the stands of *V. koschnyi* by 2.4 cm, *D. panamensis* stands by 1.4 cm, *T. amazonia* stands by 1.8 cm, *V. ferruginea* stands by 2 cm; and *H. alchorneoides* stands by 1.1 cm for managed and non-managed stands, respectively. Jacobs et al. (2005)

also found that even delayed thinning can favor *V. guatemalensis, H. alchorneoides, T. amazonia*, and *C. brasiliense* plantations. Overall, these results and data highlight the relevance, the need and the benefits of silvicultural management in native tree plantations when timber production is the main goal, even for old stands that have not been managed. However, it is recommended that landowners start managing the plantations in their earlier stages to obtain better results.

## Carbon sequestration in native tree plantations

In tree plantations economic considerations are generally more heavily weighted than in other industrial forest practices due to the higher establishment and tending costs (Hartley 2002). However, aside from timber production, tree plantations also offer other goods and services such as restoration/rehabilitation of degraded lands, wildlife habitat, watershed, and soil protection, scenic views, and carbon sequestration (Lugo and Brown 1992; Subak 2000; Shepherd and Montagnini 2001; Lamb et al. 2005). Results of the present study show that native forest plantations from 9 to 14 years old sequestered on average between 12.4 and 79.1 Mg $ha^{-1}$ of carbon. These carbon values are within the range of values that have been reported for tropical tree plantations that range between 8 and 78 Mg C $ha^{-1}$ (Schroeder 1992).

In Costa Rica, carbon sequestration has been studied over the last decade (including the species that are a part of this study) for younger plantations (Montagnini and Sancho 1994; Stanley and Montagnini 1999; Montagnini 2000; Shepherd and Montagnini 2001) and for even-age stands (Redondo-Brenes and Montagnini 2006). Results of measurements of young plantations from 4 to 8 years old showed fast-growing species such as *Jacaranda copaia* (Aubl.) D. Don. and *V. guatemalensis* to be the species with the best values for aboveground biomass (Montagnini and Sancho 1994; Stanley and Montagnini 1999; Shepherd and Montagnini 2001). At La Selva Biological Station, in tree plantations from 12 to 13 years old, Redondo-Brenes and Montagnini (2006), reported that *T. amazonia*, *C. brasiliense*, and *D. panamensis* had the highest carbon sequestration estimates. At the present research locations, in Sarapiqui, *D. panamensis* and *T. amazonia*, and in San Carlos, *D. panamensis* and *V. guatemalensis* sequestered the most carbon.

These results indicate that fast-growing species (i.e., *V. guatemalensis*) accumulate more carbon before they are 10 years old than slower-growing species. However, in the long-term slower-growing species (i.e., *D. panamensis*) accumulate more carbon than the former species. This shift in the accumulation of carbon for groups of species may be related to the wood specific gravity and growth patterns. In a study of 37 tropical species in Malaysia, Thomas (1996) suggested that canopy trees are expected to have higher height growth rates, and hence, lower wood density. Moreover, in a study of 32 neotropical species in the Amazon, Elias and Potvin (2003) found that some pioneer species such as *Ochroma pyramidale* presented some of the highest carbon values and several of the non-pioneer species exhibited some of the lowest carbon values. Thus, fast-growing species may accumulate large amounts of carbon in the first stage of their lifespan, while the high specific gravity of slower-growing species allows them to accumulate more carbon in the long-term.

The carbon sequestration values estimated in this study must be used with caution because in some plantations the range of a tree species' diameter was higher, especially for the fast-growing species, than those used by Montero and Montagnini (2005) in developing the allometric equations. Moreover, stand density and crown class (e.g., dominant, co-dominant, and suppressed) in the present study differed from the plantations where the equations were developed. These differences affect the biomass estimates of branches and foliage (Campbell et al. 1985). Furthermore, some of these equations do not consider variations in wood specific gravity within species, locations, and within individuals of the same species due to specific growth conditions (Elias and Potvin 2003; Baker et al. 2004). Some studies have reported overestimation of carbon sequestration when using allometric equations. In their study of native species growing in tree plantations in Panama and Costa Rica, Losi et al. (2003) found that the use of allometric models in a different range of trees resulted in an overestimation of 10.2% in the carbon stock values for *D. panamensis* plantations.

### Management of native tree plantations for carbon sequestration

The outcomes of the present research suggest that the seven species examined vary in their ability to sequester carbon as a result of intrinsic differences in growth characteristics and locations. Stand density is the driving factor that may explain the differences among species and locations for the carbon sequestration estimations. Data from the present study suggest that density had a positive relationship with the carbon sequestration estimations. Overall, high-density stands may sequester larger amounts of carbon than lower density stands. However, using stand density to accomplish larger aboveground carbon stocks potentially conflicts with the management treatments for timber explained in the previous section. Thus, tree plantations' objectives must be clarified before implementing reforestation programs. We can establish plantations for timber production in which we expect lower stand density, larger diameters, and lower biomass, and/or plantations for carbon sequestration objectives, with higher density and but lower timber value.

Managing native tree plantations for timber or carbon sequestration may also create conflict among local farmers, government agencies, and potential carbon offsets buyers, especially under the Kyoto protocol (Pfaff et al. 2000). Lamb et al. (2005:1629), mention that planting to generate ecological services (e.g., carbon sequestration) as well as goods (e.g., timber) is difficult, because trade-offs must be made between the productivity of the desired goods and the provision of ecological services, and the techniques to achieve these simultaneous goals are still being developed. For instance, while local farmers are receiving government incentives (e.g., PES) for establishing tree plantations in Costa Rica, most local farmers perceive plantations as a timber production tool, and only a few landowners consider their environmental services to be a unique goal (Delgado 2002; Piotto et al. 2003a). Thus, if the government agencies are evaluating the possibility of selling carbon offsets to a third party, they have to clarify the objectives of the reforestation programs and the proper manner to manage the plantations. Even tree plantations designed for timber production temporarily store carbon, until it is released into the atmosphere after the burning of the wood (Aune et al. 2005). Thus, further studies should address the net contribution of timber production plantations to soil carbon and other environmental services when trees are harvested and land uses change.

## Conclusions and implications

The results of the present research enhance the criteria elaborated in previous research findings to improve species choices for reforestation and silvicultural management in Costa

Rica and in other regions with similar ecological features. Moreover, they enhance the concept that tropical plantations can serve diverse economic, social, and ecological functions that may ultimately help reduce atmospheric $CO_2$ accumulation.

When the economic function is a priority in the reforestation program, *V. guatemalensis*, *V. ferruginea, T. amazonia*, and *H. alchorneoides* generate greater revenues in a shorter period of time than *D. panamensis*, and *C. brasiliense*. However, it is important to highlight that the differences in silvicultural management for those species resulted in large differences among plantations from the same species. Thus, silvicultural management techniques, such as thinning, must be implemented in order to improve plantation growth at both regions.

The difference in carbon sequestration values reflects two scenarios. First, if the objective is to accumulate carbon in the short-term, species such as *V. guatemalensis* and *V. ferruginea* are two of the best options due to their fast growth. On the other hand, if the objective is to create long-term carbon sinks, species such as *D. panamensis* and *C. brasiliense* are the best option. Higher density stands are also a good alternative when carbon sequestration is the main objective. Furthermore, additional research should investigate the belowground carbon contribution for native tree species. This data is lacking for native species and this information would allow us to better estimate the total carbon stock for these species.

Finally, growing native tree species in plantations is a relatively recent development in the tropics and the final rotation cycles have not been determined yet for the species included in this research. Thus, it is important to continue monitoring such plantations in order to determine the proper silvicultural treatments needed to obtain the maximum yields of those tree species as well as to determine their growth patterns when timber production is the main objective. In addition, it is important to highlight that a project on genetic improvement of some native species is being carried out for the Technological Institute of Costa Rica (TEC) and FUNDECOR. This project may provide more successful clones with better growth, better timber quality and lower production cost than the genotypes that are being used (Badilla et al. 2002). Thus, the future of native species reforestation programs in Costa Rica may be enhanced in the coming years.

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## Appendix

Appendix 1 Examples of the logarithmic regressions used to estimate total height of seven native species growing in pure plantations in Costa Rica

| Species | Location | Equation | $r^2$ |
|---|---|---|---|
| *V. guatemalensis* | Sarapiqui | H = 7.1798 × Ln(DBH) − 2.7565 | 0.9531 |
| | | H = 7.1991 × Ln(DBH) − 5.0521 | 0.7409 |
| | San Carlos | H = 10.945 × Ln(DBH) − 17.32 | 0.9901 |
| | | H = 4.8677 × Ln(DBH) + 0.048 | 0.8648 |
| *D. panamensis* | Sarapiqui | H = 10.939 × Ln(DBH) − 12.626 | 0.9137 |
| | | H = 9.5545 × Ln(DBH) − 6.4264 | 0.7889 |
| | San Carlos | H = 4.0334 × Ln(DBH) + 6.6267 | 0.9013 |
| | | H = 4.5277 × Ln(DBH) − 0.4237 | 0.6894 |
| *H. alchorneoides* | Sarapiqui | H = 5.1143 × Ln(DBH) + 3.7276 | 0.7537 |
| | | H = 14.678 × Ln(DBH) − 22.828 | 0.9902 |
| | San Carlos | H = 8.0159 × Ln(DBH) − 3.9102 | 0.8898 |
| | | H = 10.387 × Ln(DBH) − 13.02 | 0.6998 |
| *T. amazonia* | Sarapiqui | H = 8.6228 × Ln(DBH) − 5.2379 | 0.8521 |
| | | H = 5.435 × Ln(DBH) + 2.0412 | 0.7646 |
| | San Carlos | H = 17.053 × Ln(DBH) − 31.171 | 0.9867 |
| | | H = 9.9543 × Ln(DBH) − 11.094 | 0.8189 |
| *V. koschnyi* | Sarapiqui | H = 7.5388 × Ln(DBH) − 5.4846 | 0.8992 |
| | | H = 8.867 × Ln(DBH) − 6.4174 | 0.9517 |
| | San Carlos | H = 6.4628 × Ln(DBH) − 3.4483 | 0.8793 |
| | | H = 3.0224 × Ln(DBH) + 4.2413 | 0.7096 |
| *V. ferruginea* | Sarapiqui | H = 10.744 × Ln(DBH) − 14.444 | 0.7053 |
| | | H = 5.1674 × Ln(DBH) − 0.7951 | 0.8875 |
| | San Carlos | H = 3.6818 × Ln(DBH) + 3.7313 | 0.8958 |
| | | H = 18.287 × Ln(DBH) − 40.801 | 0.7665 |
| *C. brasiliense* | Sarapiqui | H = 6.4177 × Ln(DBH) − 3.0173 | 0.8994 |
| | | H = 6.6562 × Ln(DBH) − 2.1538 | 0.7971 |
| | | H = 6.6633 × Ln(DBH) − 2.9134 | 0.7456 |
| | | H = 9.7967 × Ln(DBH) − 15.056 | 0.8465 |

H, estimated total height (m); Ln, natural logarithm; DBH, diameter at the breast height (cm)

Appendix 2 Allometric models, standard error of estimate (*SEE*), correction factor (*CF*), and $r^2$-values developed by Montero and Montagnini (2005) used in the present study to estimate aboveground biomass in Costa Rica

| Species | Component | Equation | SEE | CF | $r^2$ |
|---|---|---|---|---|---|
| *C. brasiliense* | Stem | LnBiomass) = −2.570 + 2.454 × Ln(DBH) | 0.011 | 1.01 | 0.98 |
| | Branches | Ln(Biomass) = −5.773 + 3.226 × Ln(DBH) | 0.099 | 1.05 | 0.92 |
| | Foliage | Ln(Biomass) = −6.825 + 3.379 × Ln(DBH) | 0.072 | 1.04 | 0.95 |
| | Total tree | Ln(Biomass) = −2.829 + 2.704 × Ln(DBH) | 0.015 | 1.01 | 0.98 |
| *V. guatemalensis* | Stem | Ln(Biomass) = −3.867 + 2.048 × Ln (DBH) + 0.697 × Ln(H) | 0.003 | 1.00 | 0.99 |
| | Branches | Ln(Biomass) = −1.872 + 1.202 × Ln(DBH) | 0.028 | 1.01 | 0.92 |
| | Foliage | Ln(Biomass) = −4.661 + 2.014 × Ln(DBH) | 0.036 | 1.02 | 0.95 |
| | Total tree | Ln(Biomass) = −2.815 + 2.428 × Ln(DBH) | 0.044 | 1.02 | 0.97 |
| *V. ferruginea* | Stem | Ln(Biomass) = −1.776 + 1.804 × Ln(DBH) | 0.004 | 1.00 | 0.99 |
| | Branches | Ln(Biomass) = −10.100 + 4.285 × Ln(DBH) | 0.013 | 1.01 | 0.99 |
| | Foliage | Ln(Biomass) = −12.761 + 4.976 × Ln(DBH) | 0.454 | 1.26 | 0.86 |
| | Total tree | Ln(Biomass) = −3.252 + 2.492 × Ln(DBH) | 0.039 | 1.02 | 0.95 |
| *V. koschnyi* | Stem | Ln(Biomass) = −3.679 + 2.481 × Ln(DBH) | 0.013 | 1.01 | 0.98 |
| | Branches | Ln(Biomass) = −9.279 + 3.962 × Ln(DBH) | 0.098 | 1.05 | 0.96 |
| | Foliage | Ln(Biomass) = −8.988 + 3.610 × Ln(DBH) | 0.217 | 1.11 | 0.89 |
| | Total tree | Ln(Biomass) = −4.132 + 2.755 × Ln(DBH) | 0.022 | 1.01 | 0.98 |
| *D. panamensis* | Stem | Ln(Biomass) = −2.831 + 2.747 × Ln(DBH) | 0.005 | 1.00 | 0.99 |
| | Branches | Ln(Biomass) = −6.137 + 3.534 × Ln(DBH) | 0.094 | 1.05 | 0.93 |
| | Foliage | Ln(Biomass) = −6.256 + 3.197 × Ln(DBH) | 0.053 | 1.03 | 0.95 |
| | Total tree | Ln(Biomass) = −3.011 + 2.947 × Ln(DBH) | 0.006 | 1.00 | 0.99 |
| *T. amazonia* | Stem | Ln(Biomass) = −2.473 + 2.501 × Ln(DBH) | 0.011 | 1.01 | 0.99 |
| | Branches | Ln(Biomass) = −4.876 + 2.844 × Ln(DBH) | 0.044 | 1.02 | 0.99 |
| | Foliage | Ln(Biomass) = −5.456 + 2.622 × Ln(DBH) | 0.09 | 1.05 | 0.93 |
| | Total tree | Ln(Biomass) = −2.538 + 2.614 × Ln(DBH) | 0.007 | 1.00 | 0.99 |
| *H. alchorneoides* | Stem | Ln(Biomass) = −3.136 + 2.591 × Ln(DBH) | 0.029 | 1.01 | 0.96 |
| | Branches | Ln(Biomass) = −8.615 + 4.234 × Ln(DBH) | 0.027 | 1.01 | 0.98 |
| | Foliage | Ln(Biomass) = −6.404 + 2.876 × Ln(DBH) | 0.034 | 1.02 | 0.95 |
| | Total tree | Ln(Biomass) = −1.696 + 2.224 × Ln(DBH) | 0.008 | 1.00 | 0.98 |

Biomass is dry biomass in kilograms per components

DBH, diameter at the breast height (cm); H, estimated total height (m)

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