ABOVE GROUND CARBON SEQUESTRATION POTENTIAL IN MIXED AND PURE TREE PLANTATIONS IN THE HUMID TROPICS

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SHEPHERD, D. & MONTAGNINI, F. 2001. **Above ground carbon sequestration potential in mixed and pure tree plantations in the humid tropics.** The use of tree plantations for carbon sequestration can contribute to the mitigation of the increasing levels of carbon dioxide in the atmosphere. Proper design and management of plantations can increase biomass accumulation rates, making them more effective carbon sinks. The purpose of this study was to compare above ground biomass production (and subsequently carbon sequestration potential) after six years of growth between three different native tree plantations composed of pure- and mixed-species plots in the Atlantic humid lowlands of Costa Rica. In plantation 1, *Vochysia guatemalensis, Jacaranda copaia* and the four-species mixed stands had similar total biomass values, but *Calophyllum brasiliense* was significantly lower. In plantation 2, the mixed-species and the *Dipteryx panamensis* pure-species plots had higher values than the others. In plantation 3, *Hyeronima alchorneoides, V. ferruginea* and the four-species mixture had similar total biomass. Based on carbon ton-year calculations, *J. copaia* had the highest value, followed by *V. guatemalensis*, the four-species mix in plantation 1 and then by the four-species mix in plantation 2. The results of this research suggest that several native tree species in the region have a varying potential for carbon accumulation and that altering species in plantation design can influence the above ground biomass accumulation rates of tree plantations.

Key words: Biomass - carbon sinks - Costa Rica - *Dipteryx panamensis* - *Vochysia guatemalensis* - *Jacaranda copaia* - *Terminalia amazonia*

SHEPHERD, D. & MONTAGNINI, F. 2001. **Potensi sekuestrasi karbon atas tanah di ladang pokok campuran dan di ladang pokok tulen di hutan lembap tropika.** Penggunaan ladang pokok untuk sekuestrasi karbon dapat menyumbang kepada pengurangan tahap pertambahan karbon dioksida dalam atmosfera. Reka bentuk dan pengurusan ladang yang betul dapat mempertingkatkan kadar pengumpulan biojisim, menjadikannya sink karbon yang lebih berkesan. Tujuan kajian adalah

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untuk membandingkan penghasilan biojisim atas tanah (dan seterusnya potensi sekuestrasi karbon) antara tiga ladang pokok asli yang berbeza yang mengandungi petak spesies tulen dan petak spesies campuran di tanah pamah lembap di Costa Rica selepas pertumbuhan selama enam tahun. Di ladang 1, *Vochysia guatemalensis*, *Jacaranda copaia* dan dirian campuran empat spesies mempunyai nilai jumlah biojisim yang sama, tetapi jumlah biojisim bagi *Calophyllum brasiliense* adalah rendah dengan bererti. Di ladang 2, petak spesies campuran dan petak spesies tulen *Dipteryx panamensis* mempunyai nilai yang lebih tinggi daripada yang lain. Dalam ladang 3, *Hyeronima alchorneoides*, *V. ferruginea* dan campuran empat spesies kesemuanya mempunyai jumlah nilai biojisim yang sama. Berdasarkan pengiraan karbon tan-setahun, *J. copaia* mempunyai nilai tertinggi, diikuti oleh *V. guatemalensis*, campuran empat spesies di ladang 1 dan kemudian campuran empat spesies di ladang 2. Keputusan kajian ini mengesyorkan bahawa beberapa spesies asal di kawasan tersebut mempunyai potensi yang berubah-ubah bagi pengumpulan karbon dan pengubahan spesies dalam reka bentuk ladang dapat memberi kesan kepada kadar pengumpulan biojisim atas tanah bagi ladang-ladang pokok.

Introduction

Even on poor soils, tree plantations often serve an additional source of income for farmers (Gladstone & Ledig 1990, Cairns & Meganck 1994). The idea of tree plantations as a sink for carbon dioxide has gained momentum over the last decade (Andrasko 1990, Cairns & Meganck 1994). The use of tree plantations can be multi-functional: soil rehabilitation, direct economic rewards and carbon sequestration (Parrotta 1992).

Nevertheless, improved techniques, including the use of mixed-species plantations, should be tested to determine the most effective and productive use of the land for carbon sequestration, particularly in degraded lands (Brown *et al.* 1997). Moreover, well-planned mixed-species stands may provide more diverse forest products than monospecific stands and thus help decrease the risk of unstable markets to the farmer. Furthermore, in mixed stands, the faster growing species can act as a nurse for the slower growing ones and can also decrease the establishment costs for the slower species by shading out the weeds (Montagnini *et al.* 1995).

Results from previous research have indicated the capacity of the mixed-species stands to produce relatively high levels of biomass (Montagnini & Porras 1998). The present study is focused on biomass measurements of trees taken at six years to gain a better understanding of the stands at a more mature age. We expected the results of this study to be consistent with the previous research—the mixed-species stands achieving high levels of biomass production and carbon sequestration. Although it is difficult to extrapolate over a whole rotation, the results of this study suggest design and management options that could enhance the value of tropical plantations as carbon sinks and make them economically attractive to the local farmers.

Materials and methods

Study site

The tree plantations were established on an abandoned pasture at La Selva Biological Station of the Organisation for Tropical Studies, in the Atlantic humid lowlands of Costa Rica (10° 25' N, 86° 59' W, 50 m mean altitude, 26 °C mean annual temperature, 4000 mm mean annual rainfall) (Sanford *et al.* 1994). The experimental area is on flat, uniform terrain. Soils are Fluventic Dystropepts, derived from alluvially deposited volcanic materials. Soils are deep, well-drained, stone-free, with low to moderate organic matter content (2.5–4.5%), moderately heavy texture, acidic (pH < 5) and infertile (Sancho & Mata 1987). At the time of clearing, the soils were too poor for cultivation of bananas or other commercial crops commonly grown in the region (Sancho & Mata 1987). The site was manually cleared of shrubs and early successional trees before planting. The slash was left on the floor to protect against soil erosion and to inhibit the growth of weeds. Thus, neither prescribed burnings nor herbicides were used on this land.

Experimental setting

Twelve indigenous tree species of economic value were planted in three plantations in 1991–1992, each with four species. The species were selected according to growth rate, economic value, farmers' preference, nutrient-cycling characteristics and seedling availability (González *et al.* 1990, Montagnini *et al.* 1995). Plantation 1 was planted with *Jacaranda copaia, Vochysia guatemalensis, Calophyllum brasiliense* and *Stryphnodendron microstachyum*; plantation 2 with *Terminalia amazonia, Dipteryx panamensis, Virola koschnyi* and *Albizia guachapele*; and plantation 3 had *Hyeronima alchorneoides, Pithecellobium elegans, Genipa americana* and *Vochysia ferruginea.*

Each of these plantations was divided into four replicates of six randomly assigned treatment plots (32 × 32 m each). These six treatments consisted of pure plantation plots of each species, a mixed-species plot (with all four species) and a fallow (natural regrowth) plot. In each mixture of four tree species, there was at least one nitrogen-fixing tree and three other species with differing architectural structures and growth rates (Montagnini *et al.* 1995). Trees were planted in a 2 × 2 m grid. In the mixed-species plots, trees of the four species were planted by alternating two species per row.

Plantation thinnings

Following canopy closure in 1994, one half of each plot was thinned by removing all trees in every other line, leaving a 2 × 4 m distance between the trees (1250 trees ha^{-1}). The plantations were systematically thinned for the second time in 1997, by removing half of the trees that remained in each plot. The second thinning operation, in which the trees were cut in alternate rows, left the plantations at 4 × 4 m (625 trees ha^{-1}). Before thinning, trees were measured for diameter at breast height (dbh) and height to determine the averages in each plot for these characteristics. From each plot, three sample trees were selected for biomass determinations. The material from each tree was separated into different parts (stems, branches and leaves) and weighed fresh at the site. Subsamples of all materials were taken to the laboratory and dried at 70 °C to a constant weight. To obtain biomass on a per tree basis, dry:wet weight ratios were used to correct the field weight determinations based on the subsamples for each different plot and species type. Mean biomass per tree was obtained by averaging across the four replicate plots in each plantation. The average biomass per tree was multiplied by the number of trees per plot corrected for tree mortality, and extrapolated to one hectare. ANOVAs were run to compare biomass totals of tree parts for each species in mixed vs. pure plots.

Carbon accumulation was calculated for each plantation species using only stem biomass values. In addition, by limiting the analysis to the carbon storage of the stem biomass, the values can be compared to other studies in the literature. Total carbon content was calculated by assuming that stem biomass is approximately 50% carbon (Brown & Lugo 1982). The mean annual carbon increments were calculated by dividing the carbon accumulation per hectare by the respective plantation age (5–6 years). For the carbon ton-year calculations, total carbon content was based on the assumption that 50% of branch and stem dry biomass is carbon, and that 30% of dry foliage biomass is carbon. This lower calculation for carbon content for foliage is used as a conservative estimate since it is generally acknowledged that foliage contains less carbon than stemwood (Smith *et al.* 1997).

A variety of methods have been adopted for calculating carbon sequestration owing to increased interest in utilising carbon sequestration as a tool for mitigating greenhouse gas emissions. The ton-year accounting method, which calculates the ton of carbon offset per year, is the one used in this report. This method places the sequestration on a temporally weighted scale, due to the fact that the carbon does not remain "locked-up" indefinitely.

Results and discussion

Above ground tree biomass in pure and mixed plantations

In plantation 1, *V. guatemalensis*, the mixed stand and *J. copaia* had similar values for total biomass but *C. brasiliense* was significantly lower (Table 1). The total biomass of the mixture of the four species was, however, much larger (93.2 Mg ha^{-1}) than the sum of 0.25 ha of each of the species planted in the pure stands (61.2 Mg ha^{-1}).

In plantation 2, the highest total biomass per hectare was found in the four-species mixture, *T. amazonia*, *D. panamensis*, *Virola koschnyi* and followed distantly by *A. guachapele*. The sum of 0.25 ha of each of the species planted in the pure stands (59.0 Mg ha^{-1}) was lower than the total biomass of the mixture (84.7 Mg ha^{-1}).

Table 1 Above ground biomass, annual stem increment, carbon sequestration and rotation length of pure- and mixed-species plantations

	Above ground biomass (Mg ha^{-1}) Foliage	Branch	Stem	Total	Annual stem increment (Mg ha^{-1} y^{-1})	Annual carbon sequestration (Mg ha^{-1} y^{-1})	Estimated rotation length (years)
Plantation 1							
Calophyllum brasiliense	11.6 (1.8) a	16.2 (3.2) a	25.8 (2.2) a	53.5 (2.8) a	3.5	1.7	25.0
Jacaranda copaia	2.7 (0.9) b	1.0 (1.1) b	85.4 (20.1) b	89.2 (20.1) b	13.7	6.9	12.0
Vochysia guatemalensis	5.2 (1.6) c	6.8 (3.5) c	90.1 (26.8) b	102.2 (32.1) b	13.4	6.7	15.0
Four-species mixture†	5.4 (0.9) b	7.5 (1.9) b	80.3 (8.1) b	93.2 (9.1) b	13.0	6.5	18.0
Plantation 2							
Albizia guachapele	1.1 (0.1) a	4.7 (1.1) a	19.8 (4.7) a	25.7 (6.0) a	3.8	1.9	20.0
Dipteryx panamensis	5.7 (1.2) b	13.1 (2.8) b	47.3 (18.4) b	66.2 (18.7) b	6.9	3.5	20.0
Terminalia amazonia	7.4 (1.7) c	13.3 (5.3) b	58.2 (16.0) c	78.9 (20.8) c	6.7	3.3	20.0
Virola koschnyi	8.0 (1.8) c	11.5 (1.6) b	45.5 (14.9) b	65.1 (15.4) b	6.0	3.0	15.0
Four-species mixture	7.7 (1.7) c	12.0 (2.0) c	59.0 (13.1) c	84.7 (20.4) c	7.0	3.5	18.7
Plantation 3							
Genipa americana	1.7 (1.0) a	2.1 (1.2) a	12.8 (6.6) a	16.7 (8.6) a	1.5	0.8	20.0
Hyeronima alchorneoides	3.8 (1.5) b	10.0 (1.6) b	34.2 (13.7) b	48.1 (16.5) b	6.8	3.4	20.0
Pithecellobium elegans	1.8 (0.3) a	2.9 (1.1) a	20.2 (2.9) c	24.9 (4.0) c	4.1	2.1	20.0
Vochysia ferruginea	7.6 (2.7) c	11.0 (2.3) b	32.5 (6.8) b	51.1 (11.2) b	5.7	2.9	15.0
Four-species mixture	4.3 (0.7) b	10.1 (0.9) b	23.9 (3.6) c	38.3 (3.0) b	4.9	2.4	18.7

For each plantation and tree characteristic, means followed by the same letter are not significantly different.
† *Stryphenodendron microstachyum* was not thinned because of high mortality from disease (Montagnini *et al.* 1995).
Figures in parentheses are standard errors.

In plantation 3, *H. alchorneoides*, *V. ferruginea*, and the mixed-species stands all had similar values for total biomass but both the *P. elegans* and *G. americana* stands were significantly different. As in the other plantations, the sum of the biomass of 0.25 ha of each of the species planted in the pure stand (35.2 Mg ha^{-1}) was lower than in the mixed stand (38.3 Mg ha^{-1}).

It appeared that the mixed stand, with less intraspecific competition following thinning, allowed these trees more space to grow in diameter (Table 2). This is consistent with earlier research from these sites (Montagnini *et al.* 1995, Montagnini & Porras 1998). The use of faster and slower growing trees in the same plantations has the additional advantage of different rotation rates, with the slower growing species generally producing more valuable wood, representing an economic benefit. Moreover, wood from slower growing species may represent a much more long-term sink for fixed carbon than timber of less value because of its potential use in construction, furniture and woodcrafts. Due to the varying rotation lengths, the economic benefits will be more spread out, providing an additional source of income to the farmer over a longer period.

Carbon sequestration in pure and mixed plantations

The mean annual carbon increment (stemwood only) for plantation 1 ranged from 1.7 to 6.9 Mg C ha^{-1} y^{-1} (Table 1). Plantation 1 had the highest levels of carbon accumulation compared to the other plantations, with a three-fold difference between plantation 3 and twice as much as plantation 2. The range of mean annual carbon sequestration rates in plantation 2 (1.9–3.5 Mg C ha^{-1} y^{-1}) was much narrower than in the other plantations.

Based on a cumulative ton-year calculation, *J. copaia* represented 153.3 Mg C years, which was followed by the four-species mix (134.5 Mg C years) and *V. guatemalensis* (127.6 Mg C years) from plantation 1 (Table 3). Similarly, the four-species mix in plantation 2 (111.1 Mg C years) showed much higher values than the pure species stands in that plantation. In plantation 3, *H. alchorneoides* (94.8 Mg C years) had the highest value followed by the four-species stand (79.4 Mg C years). The values obtained in this study were comparable to those reported for fast growing species in humid tropical regions such as *Acacia mearnsii*, *Leucaena* spp., *Casuarina* spp., *Cassia siamea* and *Azadirachta indica* (8 to 78 Mg C ha^{-1}) (Schroeder 1992).

Forests sequester more than 92% of the world's terrestrial living carbon and store much more carbon per hectare than agricultural lands (Andrasko 1990). Young forest plantations sequester carbon at a higher rate than mature forest, though this rate of sequestration declines rapidly over time. Primary forests, however, remain an important sink for carbon and prevent the release of CO_2 to the atmosphere. Even though the forestry option has a limited impact on the CO_2 problem, a comprehensive approach should include forestation because it can still make a contribution, while at the same time, provide economic rewards to small scale farmers in developing countries from the non-carbon benefits (Sedjo 1989, Schroeder & Ladd 1991).

Table 2 Diameter at breast height (dbh) and height of tree species grown in pure and mixed conditions

	dbh (cm)	Height (m)
Plantation 1		
Calophyllum brasiliense		
Pure	10.6 (0.3) a	12.6 (5.3) a
Mixed	7.2 (1.0) b	7.8 (1.2) ac
Jacaranda copaia		
Pure	17.3 (1.8) c	18.8 (1.8) b
Mixed	24.4 (2.1) d	19.7 (1.7) b
Vochysia guatemalensis		
Pure	19.4 (1.9) c	14.3 (3.5) bc
Mixed	24.7 (1.6) d	17.1 (0.4) c
Plantation 2		
Albizia guachapele		
Pure	9.8 (1.4) a	9.0 (0.5) a
Mixed	8.3 (1.8) a	9.1 (1.8) a
Dipteryx panamensis		
Pure	10.3 (0.5) ab	13.3 (0.8) b
Mixed	12.1 (1.9) ab	13.1 (0.8) b
Terminalia amazonia		
Pure	13.1 (1.0) c	14.4 (0.8) c
Mixed	16.9 (3.5) d	14.8 (0.5) c
Virola koschnyi		
Pure	15.0 (1.9) d	11.7 (1.5) ad
Mixed	12.9 (0.9) cd	10.2 (0.8) d
Plantation 3		
Genipa americana		
Pure	7.9 (1.2) a	7.3 (0.8) a
Mixed	4.4 (1.6) b	5.5 (1.4) b
Hyeronima alchorneoides		
Pure	11.6 (0.9) c	11.4 (1.7) c
Mixed	13.1 (1.6) cd	10.9 (1.1) c
Pithecellobium elegans		
Pure	10.7 (0.2) c	9.5 (0.9) d
Mixed	11.4 (1.3) c	11.4 (1.0) c
Vochysia ferruginea		
Pure	12.6 (1.5) bc	10.3 (1.2) d
Mixed	9.5 (1.1) d	7.9 (1.0) b

For each plantation and tree characteristic, means followed by different letter are significantly different ($n = 4$, $p < 0.05$).
Figures in parentheses are standard errors.

Table 3 Calculation of carbon ton-year for each of the 12 species and the three mixed-species plots

Species	Year[a]	Carbon AI (Mg)	Standing crop C (Mg)[b]	Cumulative ton-years
Plantation 1				
Calophyllum brasiliense	1	2.7	2.7	2.7
	2	2.7	5.5	8.2
	3	2.7	8.2	16.4
	4	3.9	12.1	28.5
	5	3.9	15.9	44.4
	6	3.9	19.8	64.2
Jacaranda copaia	1	7.6	7.6	7.6
	2	7.6	15.3	22.9
	3	7.6	22.9	45.8
	4	6.5	29.4	75.2
	5	6.5	35.8	111.0
	6	6.5	42.3	153.3
Vochysia guatemalensis	1	4.3	4.3	4.3
	2	4.3	8.5	12.8
	3	4.3	12.8	25.6
	4	10.6	23.4	49.0
	5	10.6	34.0	83.0
	6	10.6	44.6	127.6
Four-species mixture	1	5.2	5.2	5.2
	2	5.2	10.3	15.5
	3	5.2	15.5	31.0
	4	9.5	25.0	56.0
	5	9.5	34.5	90.5
	6	9.5	44.0	134.5
Plantation 2				
Albizia guachapele	1	1.7	1.7	1.7
	2	1.7	3.4	5.1
	3	1.7	5.1	10.2
	4	2.9	8.0	18.2
	5	2.9	10.9	29.1
	6	2.9	13.8	42.9
Dipteryx panamensis	1	4.6	4.6	4.6
	2	4.6	9.3	13.9
	3	4.6	13.9	27.8
	4	4.2	18.1	45.9
	5	4.2	22.2	68.1
	6	4.2	26.4	94.5
Terminalia amazonia	1	5.2	5.2	5.2
	2	5.2	10.3	15.5
	3	5.2	15.5	31.0
	4	3.1	18.6	49.6
	5	3.1	21.6	71.2
	6	3.1	24.7	95.9
Virola koschnyi	1	4.0	4.0	4.0
	2	4.0	8.1	12.1
	3	4.0	12.1	24.2
	4	3.8	15.9	40.1
	5	3.8	19.7	59.8
	6	3.8	23.5	83.3

Continued

Table 3 (continued)

Species	Year[a]	Carbon AI (Mg)	Standing crop C (Mg)[b]	Cumulative ton-years
Four-species mixture	1	6.2	6.2	6.2
	2	6.2	12.5	18.7
	3	6.2	18.7	37.4
	4	2.9	21.6	59.0
	5	2.9	24.6	83.6
	6	2.9	27.5	111.1
Plantation 3				
Genipa americana	1	3.0	3.0	3.0
	2	3.0	5.9	8.9
	3	3.0	8.9	17.8
	4	-1.5	7.4	25.2
	5	-1.5	6.0	31.2
	6	-1.5	4.5	35.7
Hyeronima alchorneoides	1	5.8	5.8	5.8
	2	5.8	11.6	17.4
	3	5.8	17.4	34.8
	4	1.3	18.7	53.5
	5	1.3	20.0	73.5
	6	1.3	21.3	94.8
Pithecellobium elegans	1	5.5	5.5	5.5
	2	5.5	10.9	16.4
	3	5.5	16.4	32.8
	4	-1.6	14.8	47.6
	5	-1.6	13.2	60.8
	6	-1.6	11.6	72.4
Vochysia ferruginea	1	5.0	5.0	5.0
	2	5.0	9.9	14.9
	3	5.0	14.9	29.8
	4	0.1	15.0	44.8
	5	0.1	15.2	60.0
	6	0.1	15.3	75.3
Four-species mixture	1	5.0	5.0	5.0
	2	5.0	10.0	15.0
	3	5.0	15.0	30.0
	4	0.7	15.7	45.7
	5	0.7	16.5	62.2
	6	0.7	17.2	79.4

Stryphenodendron microstachyum was not thinned because of high mortality from disease.

[a] Years 3 and 6 are actual data, the values listed for the other years are interpolated from these two data points.

[b] Based on the assumption that carbon is 50% of stem and branch biomass and 30% of foliage biomass.

AI = Annual index

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