

Bactris gasipaes agroecosystems for heart-of-palm production in Costa Rica: changes in biomass, nutrient and carbon pools with stand age and plant density

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Abstract

Perennial tree crops develop through growth phases that differ in the rate of biomass and carbon build-up, and in the relative contribution of various pools and fluxes to nutrient cycles and nutrient supply for plant growth. To define these phases in peach palm (*Bactris gasipaes*) agroecosystems for heart-of-palm production, we estimated biomass in stands up to 20 years of age in the humid tropical lowlands of Costa Rica. Dry biomass of foliage, petioles and stems were estimated using allometric equations which have been previously generated by applying nonlinear seemingly unrelated regression procedures to data from harvests of peach palm plants. Total aboveground biomass trajectories through time were fitted by a three-parameter logistic function with total biomass stabilizing at about 6.3 Mg/ha. There were no differences in standing biomass between stands on Andisols and Ultisols. Trends in nutrient pools through time were similar to those for biomass. The order in size of nutrient pools was N (up to approximately 120 kg/ha) > K (up to 90 kg/ha) > Ca (up to 45 kg/ha) > Mg, S, P (all up to 15–17 kg/ha). Peach palm plant bases and coarse roots are relatively large fractions of total plant biomass, and consequently of sequestered carbon and nutrients. The amount of carbon per unit area in plant tissue in peach palm agroecosystems in the Atlantic region of Costa Rica was about 8% of the carbon in forests of the same region. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Peach palm; Biomass and nutrient budgets; Carbon sequestration

1. Introduction

The prolonged growth span of perennial tree crops has fundamental implications for carbon and nutrient storage, and for nutrient cycling in agroecosystems. Perennial tree crops have distinct phases which differ

in the rate of aboveground and belowground biomass accumulation, and in the relative contribution of various pools and fluxes to nutrient cycles. Biomass accretion relative to the standing biomass is usually maximum during a period between the initial growth phase (i.e. establishment) and that in which a relative equilibrium in stand biomass is reached (Blackman, 1968). Among nutrient cycling processes, nutrient retranslocation becomes a more important component of the cycle as the crop age increases (Miller, 1984). Thus, the identification of growth phases is important for calculating nutrient and carbon budgets and, in

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developing diagnosis, prediction and economic analyses for integrated nutrient and crop management. The onset and duration of the growth phases in perennial tree crops are often not self-evident because they depend upon species growth patterns and phenology, stand density and crop management. These growth phases have to be determined separately for almost every tree crop and apply to a given set of management conditions and geographical areas.

Peach palm (*Bactris gasipaes*) for heart-of-palm has become an important perennial crop in the humid tropics of Latin America (Mora Urpí et al., 1997; Deenik et al., 2000), where it is mostly grown on Andisols, Oxisols and Ultisols in Costa Rica and Brazil. Peach palm is a caespitose, usually spiny palm that continuously produces new shoots that are purposely controlled in number to optimize production. Harvest for heart-of-palm begins at 1 or 1.5 years, and continues during the life of the stand which may surpass 20 years. Four growth stages have been described for palms: embryonic, seedling, establishment, adult vegetative and adult reproductive (Tomlinson, 1990). In peach palm stands for heart-of-palm, the first two of these phases take place in the nursery, and only the establishment and adult-vegetative phases occur in the field. During the establishment phase which extends from planting to approximately the first harvest, peach palm produces bifid eophyll and later pinnate leaves while the adult vegetative phase starts at the beginning of stem elongation and lasts until the first flowering (Clement, 1995), a phenological event that does not take place in heart-of-palm production. For purposes of developing management recommendations for fertilization and control of shoot density, the growth stages in heart-of-palm production with this species can be divided into establishment, fast growth and maturity. In the context of this study, the term maturity refers to the stage in which a stabilized level of biomass is reached. The span of these growth phases in peach palm stands of varying stand density and grown on different soil types in the Atlantic region of Costa Rica was unknown.

In recent years, stand density of peach palm in the Atlantic region of Costa Rica has been consistently increased from a traditional level of less than 4200 plants/ha (spacings at 2.50–2.65 m × 1 m) to 10 000 plants/ha (2 m × 0.5 m), or more. We hypo-

thesized that the onset and duration of growth phases are modified by stand density. On the other hand, we anticipated that soil type would have a minor effect on growth trajectories because soil nutrient status is rather uniform as a result of fertilizer application, and drought stress is unlikely in the Atlantic region of Costa Rica.

Previous biomass estimates in peach palm stands were site-specific and provided only an indication of trends in biomass accumulation because of the reduced size of plant samples and stand ages. In Hawaii, above-ground biomass at 1.3 years ranged between 0.45 and 1.40 kg of dry matter per plant (roughly 2–7 Mg/ha) in peach palm experimental plots with a density equivalent to 5000 plants/ha (Clement, 1995). In Costa Rica, harvest of a few plants from a 3-year-old stand with 3200 plants/ha, yielded 7.1 Mg/ha of standing dry biomass (Herrera, 1989).

Belowground biomass may account for an important proportion of total biomass in peach palm stands especially as stand age progresses. Peach palm has shallow and coarse roots with 58–80% of the root biomass found in the top 20 cm of the soil (Ferreira et al., 1980, 1995; López Morales and Sancho Vargas, 1990; Jongschaap, 1993), but total belowground biomass has not been estimated in the field. The roots, the rhizome and a fibrous tissue below the base of the stem form a clump which increases in size with time. We, therefore, hypothesized that belowground biomass may surpass that of aboveground biomass in mature stands.

Because of the large annual biomass production, we also hypothesized that soil organic carbon may increase with extended cropping. Plant residue production measured during 48 weeks in 4–5-year-old peach palm stands averaged 11.4 Mg/ha of dry biomass (Molina, personal communication). The test of the hypothesis was not strictly rigorous in this study because the initial soil organic carbon values were unknown. If effects on soil are strong, however, it may be possible to find significant differences with time. On the other hand, continued fertilization is likely to decrease soil pH and exchangeable cations, and increase exchangeable acidity. In a fertilization experiment on a Typic Dystrandepet in Costa Rica with N:P:K applications up to 550:87:225 kg/ha per year, respectively, soil pH decreased from 5.5 to 4.5, and exchangeable acidity increased from 0.30 to

1.21 meq/100 g while Ca, Mg and K decreased after 48 months of heart-of-palm production (Guzmán, 1985).

The size of the carbon pools in peach palm stands is also important given the current interest in carbon sequestration in the tropics. Some landowners in Costa Rica are already receiving compensation for preserving forests, and research on the soil and plant carbon sequestering potential of agricultural systems in the region is underway (Bulte et al., 2000). In terms of area, peach palm is the second most important perennial crop in the Atlantic region of Costa Rica after banana comprising some 12 000 ha, while the total area of peach palm in Central and South America is about 24 000 ha (Mora Urpí et al., 1997).

The objectives of this study were to (i) estimate aboveground biomass and nutrient pools in peach palm stands for heart-of-palm production on a range of stand ages and soil types, (ii) define growth phases based on patterns of standing biomass and plant and shoot density, (iii) estimate the amount of belowground relative to aboveground biomass, and (iv) infer potential impacts on soil from long-term cultivation of peach palm and derive estimates of carbon status in plant and soil.

2. Materials and methods

2.1. Aboveground biomass and nutrient pools

We selected 18 peach palm stands within either large farms belonging to an agribusiness company or small farms throughout the Atlantic region of Costa Rica. Mean annual rainfall of the region varies between 4000 and 5000 mm per year while mean annual temperature is about 24.5 °C. The selected stands were all of the Utilis-Tucurrique thorny landrace and were on Andisols and Ultisols (Soil Survey Staff, 1999), except one stand that was on an Inceptisol.

In each selected field, we chose one row and one plant within the row by using a random number table. The chosen plant was the approximate center of a rectangular 200 m² plot with the longest side parallel to the crop rows. We avoided measurements on field borders. On every individual shoot within the plot, we measured basal diameter at 5 cm aboveground and height to the fork between the first fully expanded leaf and the spear leaf. We then used allometric equations

(Ares et al., 2001) generated by a non-linear regression procedure (Parresol, 1999) to calculate the aboveground component and aboveground total plant biomass as a function of shoot basal diameter. With this regression method, plant component estimates add up to the aboveground total plant biomass and also, residuals are modeled to ensure equal error variances through the range of the independent variable. Biomass estimates from the equations were similar to data from independent harvests (Ares et al., 2001).

We tested the fit of different regression models to biomass data from low (<4200 plants/ha) and high density (>4200 plants/ha) stands using the NLIN procedure in the Statistical Analysis System Package (SAS Institute Inc., 1989) and SigmaPlot 5.0 (SPSS Inc., Chicago, USA). For early stages, we included data from a previous study conducted during 132 days in a stand with 4000 plants/ha on an Andisol in one of the farms we sampled (Jongschaap, 1993). We were not able to find stands with more than 6000 plants/ha older than 5.7 years because planting high density stands is a relatively recent trend in peach palm agroecosystems in Costa Rica. To fit the equations, we assumed that stands with more than 4200 plants/ha reach the same maximum biomass than stands with less than 4200 plants/ha. We also included the data recorded until a stand age of 132 days for both equations because plant competition was likely nil or minimum at this early stage.

Composite subsamples of each plant component were randomly selected, taken to the laboratory, dried at 75 °C to constant weight and ground to pass a 0.40 mm sieve. Plant component samples were analyzed for total concentration of N by a micro-Kjeldahl procedure (Nelson and Sommers, 1972), for Al, Na, Ca, Mg, K, Fe, Mn, Cu and Zn by atomic absorption spectrophotometry, and for B with the azomethine-H method (Wolf, 1974). Phosphorus was determined with UV spectrophotometry after stannous chloride reduction of the phospho-molybdate complex (Chapman and Pratt, 1973) and S with a Lachat flow injection analyzer. Sulfur was determined only in 11 stands.

In each plot, we also sampled soil at 0–5 and 5–20 cm depths from 10 positions within each plot. The soils were dried at 60 °C, ground to pass a 2 mm sieve, and analyzed for organic C by the Walkley and Black method (Nelson and Sommers, 1972), for total N by a micro-Kjeldahl procedure, and for K, Zn, Cu,

Fe and Mn by atomic absorption spectrophotometry after extraction following the modified Olsen method. Phosphorus was determined colorimetrically by the Murphy and Riley procedure (Murphy and Riley, 1962). After extraction with KCl, Ca and Mg were determined by atomic absorption spectrophotometry, and acidity by titration with NaOH. Sulfur and B were determined with a Lachat flow injection analyzer. Soil pH was measured in a 1:2.5 soil:water suspension and soil organic matter was determined by the Walkley and Black method.

2.2. Belowground biomass and nutrient pools

In a separate sampling, we uprooted 11 peach palm plants in four stands ranging in age from 1.9 to 21 years. Initial spacing in the sampled stands was 2 m × 0.5 m except the 21-year-old stand which had a spacing of 2.6 m × 1 m. In most cases, the soil was dug to 80 cm depth to remove the roots. The belowground mass was taken intact to the laboratory, washed to remove soil and separated manually into two components: basal section and coarse roots. The term 'basal section' refers to the rhizome and the fibrous tissue below the stem. Moisture and nutrient content were determined in subsamples of the two components. For nutrient tissue analysis, we used the same procedures as applied to aboveground biomass.

To determine the relationship between aboveground and belowground biomass, shoots of the selected plants were cut at ground level, separated into foliage, petiole and stem, and weighed in the field after we measured basal diameter and height to the spear leaf. Subsamples were taken to the laboratory for fresh:dry weight ratio determination.

2.3. Carbon pools

We present an example of the amount of carbon in a mature peach palm stand on an Andisol and an Ultisol using the average carbon content of the sampled Andisols and Ultisols in this study, and a soil bulk density of 0.8 and 1.2 g/cm³ (Salas, personal communication), respectively. Aboveground and belowground biomass corresponded to a stand that has reached the maturity stage. Aboveground plant biomass of stands on Andisols was the same as that on Ultisols as indicated by this study. Plant biomass

values were converted to carbon amounts by using a fraction of carbon in dry biomass of 0.45 (Barbour et al., 1987). This coefficient is approximate and it can vary among systems. For instance, a coefficient of 0.50 was used by Cannel et al. (1996). To estimate standing in plant residues, we assumed an annual residue production of 11.4 Mg/ha equally distributed throughout the year, and decomposing at the rate measured in a related study (Molina, personal communication).

3. Results

3.1. Characteristics of the sampled peach palm stands

Plant density ranged between 3150 and 7250 plants/ha while shoot density varied between 4000 and 24 250 shoots/ha (Table 1). Average number of shoots per plant was 3.31. For stands older than 1 year, 69% of the stands had between two and four shoots

Table 1
Characteristics of the peach palm stands for heart-of-palm production measured in the Atlantic region of Costa Rica

Site	Soil	Stand age (years)	Plant density (plants/ha)	Shoot density (shoots/ha)
Río Frio	U ^a	1.0	3650	4000
Guápiles	A ^b	1.0	6150	6150
Guápiles	A	1.5	5550	20150
La Conquista	U	1.7	5400	14950
Río Frio	U	2.0	5750	15150
Guápiles	A	2.2	7250	9500
Horquetas	A	2.7	6500	22000
Huetares	U	3.6	4450	12700
Guápiles	A	5.0	3150	12050
Guápiles	A	5.2	4550	17400
Río Frio	I ^c	5.7	6400	15000
Guápiles	A	7.5	3750	10700
Río Frio	U	9.0	3700	24250
Guápiles	A	10.0	3700	13750
Río Frio	U	14.5	4700	12700
Guápiles	A	15.0	3950	19750
Río Frio	U	20.0	4150	19000
Guápiles	A	20.0	3250	18100

^a Ultisols.

^b Andisols.

^c Inceptisols.

per plant, a range that likely reflects proper density management.

3.2. Aboveground biomass and nutrients

There were no differences in biomass between stands on the different soil types and thus the data were pooled for further analysis. Total aboveground biomass trajectories were fitted by three-parameter logistic functions with total biomass reaching a maximum at 6.31 Mg/ha (Fig. 1). The equations were

$$AB = \frac{6310}{1 + (\text{age}/4.672)^{-1.258}} \quad (1)$$

for stands with <4200 plants/ha, S.E.E. = 497.1 and $P < 0.0001$, and

$$AB = \frac{6310}{1 + (\text{age}/0.990)^{-1.347}} \quad (2)$$

for stands with >4200 plants/ha, S.E.E. = 707.9 and $P = 0.0056$. Here AB is the total aboveground biomass (kg/ha) and S.E.E. is the standard error of estimate in actual units.

Half the maximum biomass was reached at age 4.7 years in stands with less than 4200 plants/ha, and at about age 1 year in stands with more than 4200 plants/ha, reflecting a steep increase in biomass

accumulation during the initial growth period in high-density stands. Based on these trends, we proposed the following growth phases in peach palm stands for heart-of-palm:

- Establishment: 0–1 years. The stand is not yet harvested for heart-of-palm.
- Fast growth: 1–3 years in high-density stands and 1–8 years in low-density stands. Biomass accretion and heart-of-palm production increase.
- Maturity: The stand reaches a level of stabilized biomass and heart-of-palm production.

The order in nutrient pools was N (up to approximately 120 kg/ha) > K (up to 90 kg/ha) > Ca (up to 45 kg/ha) > Mg, S, P (all up to 15–17 kg/ha) (Table 2). One stand had unusually large N and K pools and was likely not representative. Trends in nutrient pools through time suggested logistic or parabolic trajectories but no meaningful function fitted the data probably because of lack of values for early stand ages. Data for plant micronutrients are not shown.

3.3. Belowground biomass and nutrients

In the separate sampling of four stands, the trajectory of the ratio of belowground to aboveground biomass through time fitted a rectangular, two-parameter hyperbola and varied between one in the young stand

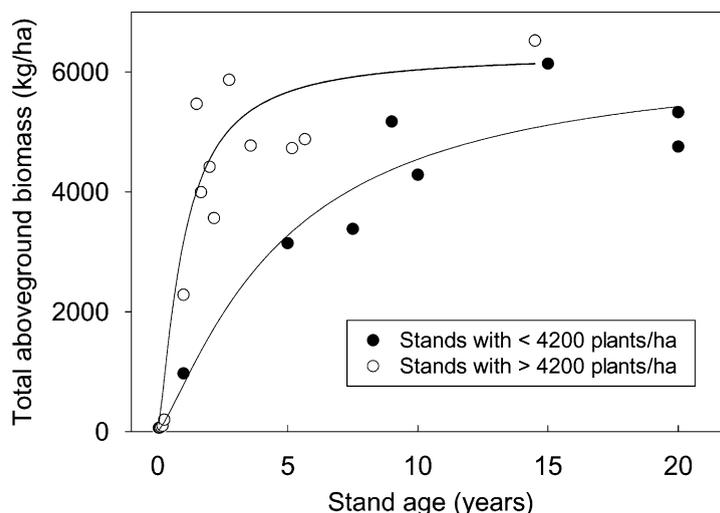


Fig. 1. Standing biomass through time in peach palm stands. The aboveground biomass is calculated using Eqs. (1) and (2). Data points close to the origin of coordinates are from a separate study carried out during 132 days in the same area (Jongschaap, 1993).

Table 2
Aboveground pools of N, P, K, Ca, Mg and S in peach palm stands

Site	Stand age (years)	N	P	K (kg/ha)	Ca	Mg	S
Río Frio	1.0	20.0	2.2	14.9	4.7	2.8	1.9
Guápiles	1.0	37.7	5.3	9.3	14.2	5.1	–
Guápiles	1.5	149.0	11.8	118.6	17.4	11.6	10.3
La Conquista	1.7	51.2	7.7	46.8	21.3	10.0	–
Río Frio	2.0	85.3	14.2	66.0	23.0	11.5	15.3
Guápiles	2.2	66.2	8.4	32.7	24.4	8.4	–
Horquetas	2.7	74.9	15.2	62.5	31.4	17.0	–
Huetares	3.6	72.9	11.4	55.7	26.0	12.9	–
Guápiles	5.0	71.3	6.4	55.7	13.4	5.7	5.8
Guápiles	5.2	55.2	13.2	70.8	19.2	11.5	–
Río Frio	5.7	92.8	11.3	31.0	30.6	13.3	–
Guápiles	7.5	75.3	7.5	35.0	17.9	8.5	12.9
Río Frio	9.0	96.5	14.9	86.6	22.5	9.9	16.2
Guápiles	10.0	101.0	9.3	69.5	17.4	10.8	11.7
Río Frio	14.5	96.0	14.1	68.5	44.7	13.5	13.6
Guápiles	15.0	118.1	7.9	50.2	25.1	12.1	9.8
Río Frio	20.0	93.1	11.6	54.4	23.7	7.7	8.2
Guápiles	20.0	96.5	11.4	88.2	17.1	8.5	12.7

to more than two in the oldest stand (Fig. 2). On a ground area basis, therefore, there may be more than 10 Mg/ha of belowground biomass in a mature peach palm stand compared to 5.5 Mg/ha of aboveground biomass. The estimate excludes fine roots and may therefore underestimate actual belowground biomass. The abundance of fine roots, however, was remarkably low in the sampling sites (personal observation).

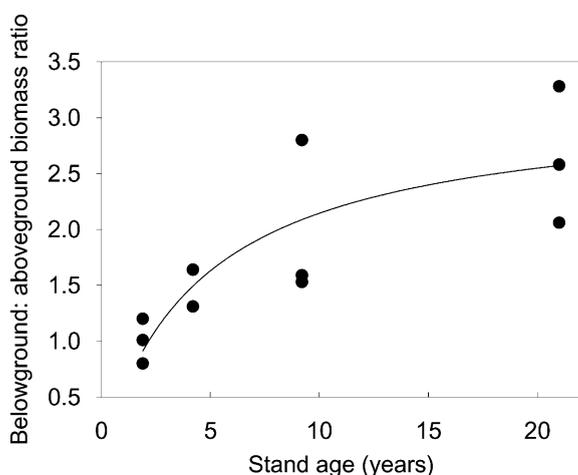


Fig. 2. Belowground:aboveground biomass ratio (BAR) in peach palm stands. The hyperbolic function is $BAR = (3.139 \times \text{time} / 4.628) + \text{time}$ (S.E.E. = 1165.1, $P = 0.0018$).

The proportion of nutrients in belowground biomass increases with age (Table 3). There is a trend to a lesser proportion of N, K, Ca and Mg in coarse roots than in the basal section with the exception of P.

3.4. Soil characteristics and carbon status through time

There were no significant changes with stand age in soil organic carbon (Fig. 3). In stands older than 2

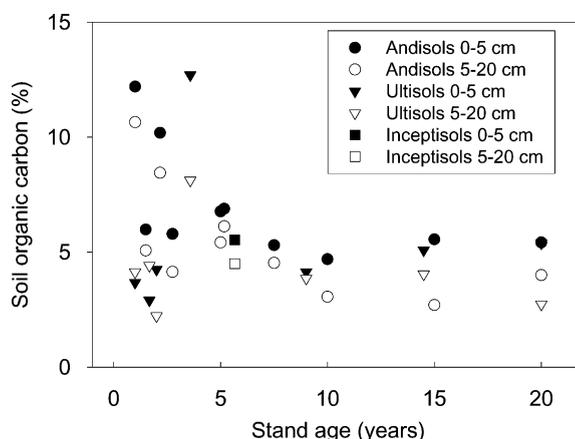


Fig. 3. Soil organic carbon concentration at 0–5 cm depth in peach palm stands.

Table 3

Macronutrient content (%) in belowground tissues in peach palm stands. The ratios between belowground and aboveground quantities of the nutrient are in parentheses.

Stand age (years)	N	P	K	Ca	Mg
Basal section					
1.9	1.12 (0.24)	0.27 (0.53)	0.52 (0.28)	0.22 (0.13)	0.14 (0.36)
4.2	0.61 (0.34)	0.09 (0.24)	0.31 (0.42)	0.17 (0.21)	0.10 (0.28)
9.2	0.90 (0.53)	0.24 (0.48)	0.78 (0.80)	0.37 (0.70)	0.12 (0.73)
21.0	0.46 (1.08)	0.29 (1.50)	0.59 (0.73)	0.18 (0.92)	0.13 (1.14)
Coarse roots					
1.9	0.62 (0.20)	0.20 (0.59)	0.53 (0.31)	0.15 (0.13)	0.08 (0.43)
4.2	0.32 (0.18)	0.10 (0.26)	0.28 (0.37)	0.23 (0.28)	0.08 (0.22)
9.2	0.50 (0.27)	0.21 (0.81)	0.52 (0.50)	0.17 (0.30)	0.10 (0.57)
21.0	0.47 (0.38)	0.50 (0.93)	1.07 (0.47)	0.23 (0.41)	0.17 (0.52)

Table 4

Estimates of aboveground and belowground carbon in mature peach palm stands for heart-of-palm production on an Andisol and an Ultisol in the Atlantic region of Costa Rica

Store	C (kg/ha)
Aboveground	2400
Belowground	4800
Plant residues	830
Soil (0–20 cm)	83000 ^a , 88800 ^b
Total	91039 ^a , 96830 ^b

^a Andisol.

^b Ultisol.

years of age, soil organic carbon at 0–5 cm averaged about 5.5% for Andisols and 3.7% for Ultisols. As an example, in a mature peach palm stand there is approximately 8.0 Mg C/ha in aboveground biomass and, in the topsoil, 83 Mg C/ha in Andisols and 89 Mg C/ha in Ultisols (Table 4). Also, soil pH, exchangeable acidity, and soil macro and micronutrients did not vary with stand age (data not shown).

4. Discussion

Standing biomass in peach palm stands for heart-of-palm increased with time following a logistic trend. Stand density modified the duration of growth phases with low density stands reaching the maximum biomass of about 6.3 Mg/ha at a greater age than high density stands. On the other hand, maximum biomass was not strongly affected by soil type. Additional data

from a wider range of stand densities would allow to develop biomass models as a function of both age and plant density although the scarcity of relatively old high density stands remains a methodological problem.

Nutrient quantities in peach palm stands were approximately proportional to the amounts of standing biomass. This is expected because, unlike to other tree crop systems, standing biomass in peach palm stands regenerates continuously after harvests. In forest vegetation, part of the aboveground biomass is not renewable and continues to increase during an extended period. Therefore, the rate of accumulation for different nutrients may change during the rotation as noted, for example, in *Eucalyptus* stands where Mg accumulated during early stages while P and Ca increased in proportion to the stand biomass throughout the rotation (Laclau et al., 2000).

Aboveground nutrient stocks approximately followed the presumed order in nutrient needs (N > K > Ca > Mg, S, P) suggested by previous studies except probably for Mg. Growth responses of peach palm to N and K additions have been recorded (Guzmán, 1985; Pérez et al., 1993; Lopes Reis, 1997) but responses to P have been infrequent. It is important to note, however, that responses to nutrient inputs do not always relate to internal plant needs. Peach palm often shows visual symptoms of Mg deficiency suggesting a relatively high requirement for this element although Mg deficiency may also occur because imbalances with other nutrients such as K (Smyth, personal communication).

Increased proportion of belowground biomass with time indicated that belowground tissues continue to grow after the standing biomass reaches a relatively steady state. Belowground biomass appears to increase until belowground plant organs occupy most of the available horizontal space between plants. A high concentration of nutrients such as P in belowground tissues compared to aboveground biomass suggests that the basal section and the coarse roots are large nutrient sinks.

The lack of effect of long-term peach palm cultivation on soil pH contradicted previous results (Guzmán, 1985) that indicated soil acidification and depletion of bases after 4 years of fertilization. Lack of effect on soil pH may be in part attributable to modest doses of nitrogenous fertilizers and the replacement of urea by other fertilizer types, as well as to possible applications of lime materials in peach palm stands. The study did not provide evidence of soil organic carbon enrichment with time under the peach palm stands. Conversely, in the San Carlos plains of Costa Rica, topsoil carbon was 8 and 14% higher under a 18.5-year-old secondary forest than in 12.5- and 3.5-year-old secondary forests with similar histories and on the same soil type (Guggenberger and Zech, 1999). In an alley cropping system in Indonesia in which soil carbon was measured initially, soil carbon was maintained after 7 years by the presence of multipurpose trees but it decreased without tree intercropping (Evensen et al., 1995). In Brazil, soil carbon stocks at 0–30 cm depth under a continuously grazed pasture of *Brachiaria humidicola* increased from 44.5 to 49.3 Mg/ha after 9 years (Tarré et al., 2001).

Carbon stored in aboveground biomass at a given point in time in peach palm stands for heart-of-palm production is considerably lower than in forest vegetation in the Atlantic region of Costa Rica. Average carbon stored in forest vegetation in the same region was 100 Mg C/ha (Bulte et al., 2000), more than 10-fold the carbon in peach palm stands. For temperate areas, average amounts of 14.1 Mg C/ha for young coniferous stands and of 46.6 Mg C/ha in broadleaved woodlands have been reported (Cannel and Milne, 1995) while amounts of carbon in agroforestry systems ranged between 9 and 50 Mg C/ha (Schroeder, 1994). Also, carbon in aboveground biomass is retained during a short time in peach palm stand owing the continuous harvest but carbon sequestered in belowground

biomass would remain longer than in aboveground tissues. Nonetheless, the turnover rate of peach palm roots in the Atlantic region of Costa Rica is likely high. Non-functional, necrotic roots in a peach palm stand on an Andisol accounted for 37% of the root biomass up to 1 m in soil depth (López Morales and Sancho Vargas, 1990).

We estimated that there is about 91–97 Mg C/ha in a mature peach palm stand including only the upper 20 cm of the soil profile in the calculation. Studies of carbon storage profiles, however, indicated that 40–60% of the soil carbon can be stored below 25 cm depth (Arrouays and Pelissier, 1994). Therefore, there may be 130–140 Mg C/ha in a mature peach palm stand.

Overall, this study on peach palm agroecosystems for heart-of-palm production revealed the effect of age and spacing on patterns of stand biomass. Belowground biomass appears partially coupled to aboveground biomass pools because root turnover rates may be related to aboveground management but also interplant competition would develop relatively late in the age of the stand to restrict belowground growth. Commercial production of heart-of-palm seemed neither to induce detrimental effects on soil characteristics nor measurable increases in soil organic carbon.

5. Conclusion

The onset and duration of growth phases in peach palm were modified by stand density but not by soil type. Based on the available information, the proposed growth phases in peach palm stands for heart-of-palm are as follows:

- Establishment: 0–1 years.
- Fast growth: 1–8 years in low density stands and 1–3 years in high density stands.
- Maturity or level of stabilized biomass.

Relatively large amounts of carbon and nutrients are underground in peach palm stands with the aboveground:belowground ratio decreasing with stand age. The study did not provide evidence of strong effects on soil characteristics or soil organic carbon build-up from peach palm cultivation but at least soil organic matter stocks remained stable after long-term cropping. Overall, the amounts of carbon stored in peach

palm agroecosystems in the Atlantic region of Costa Rica seem modest compared to secondary forests in the same region.

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