

Nutrient fluxes and growth of *Carapa guianensis* Aubl. in two plantation systems in the central Amazon

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Abstract

The K, Mg, and P fluxes as well as the growth dynamics of the important timber tree *Carapa guianensis* Aubl. were compared in a monoculture and in an enrichment plantation on a “terra firme” site near Manaus, central Amazon.

During the 7 years experimental period, the K, Mg, and P fluxes and the balance of the soil were quantified for monthly intervals. The nutrient input into the soil was calculated from the wet and dry deposition as well as from litter decomposition. The nutrient output out of the soil was calculated from the net nutrient uptake of the vegetation and the nutrient leaching from the soil. The growth dynamics of the planted trees were studied by means of biomass data obtained from dendrometric measurements and total tree harvesting.

After 7 years of growth, the K, Mg, and P balance of the soil of the enrichment plantation was stabilised, whereas a significant deficit of the K, Mg, and P balance of the soil of the monoculture became obvious, caused by high leaching of K and Mg from the soil and low litter decomposition rates. Due to strong competition during the first 5 years of growth, a reduced biomass production of the planted *Carapa* trees was found in the enrichment plantation compared to trees grown in the monoculture. After that period tree growth was strongly reduced in the monoculture, whereas after 7 years, growth of *Carapa* grown in the enrichment plantation was still steady.

From this study, it was concluded that due to the balanced K, P, and Mg input and output of the soil and more sustainable growth of the planted trees in the enrichment plantation compared to the traditional monoculture, the cultivation of *Carapa* for timber production is recommended in diverse plantations, such as enrichment plantations on this study site. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Monoculture; Enrichment plantation; Nutrient balance (K, Mg, P); Growth pattern

1. Introduction

In the central Amazon, the demand for wood for the local market and for export is exclusively satisfied from primary forests, which leads to strong

exploitation especially of high quality species (Loureiro et al., 1979; Rizzini, 1990; Fearnside and Ferraz, 1995). In addition, logging in primary forests is often associated with serious negative affects on the ecosystem “tropical forest” (Lamprecht, 1986; Brünig, 1996) and with a degradation of the soil (Fernandes et al., 1997). As to counteract this tendency, during the last years, in the central Amazon, special attention was given to the cultivation of tree species for high quality timber production in plantation systems (Lamprecht, 1986;

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Whitmore, 1995; Brünig, 1996; Bauch et al., 1999). Nevertheless, the knowledge about the site demands of native timber tree species and the appropriate management of timber plantations is still restricted in the Amazon.

Besides genetic factors, tree growth depends on a sufficient light, water, and mineral element supply of the trees (Kozłowski et al., 1991; Larson, 1995). In large areas of the central Amazon, tree growth is limited by the restricted mineral element supply of the soils (Klinge, 1976; Drechsel and Zech, 1991). Recent field studies exhibited especially a strong lack of K, Mg, and P on “terra firme” sites of this region (Jordan, 1982; Fernandes et al., 1997; Dünisch et al., 1999a; Schroth et al., 2000).

As a rule, traditional monoculture plantations cause nutrient imbalance and strong nutrient loss of the soil, due to the “slash and burn” management for site preparation (Hölscher et al., 1997) and the low nutrient fixation in the biomass (Dünisch and Schwarz, 2001). This often leads to low productivity of monoculture plantations in the long run (Williams and Melack, 1997). As to counteract these problems, enrichment plantation systems in existing primary or secondary vegetation are discussed as an alternative for sustainable wood production in plantations of the tropics (Lamprecht, 1986). However, the native vegetation of enrichment plantations is a strong competitor for the planted trees (Azevedo et al., 1999), which might lead to a strong reduction in productivity of the planted trees in enrichment plantations compared to monoculture plantation systems.

In this comparative study, the K, Mg, and P fluxes as well as the growth dynamics of a 7-year-old enrichment plantation and a traditional monoculture plantation of the high quality timber tree *Carapa guianensis* Aubl. (Gottwald, 1961; Wagenführ and Scheiber, 1985; Bauch and Dünisch, 2000) were investigated. Special regard was given to the stabilisation of the nutrient balance of the plantation and the sustainability of wood production.

2. Materials and Methods

2.1. Study site and plantation systems

The study was carried out on the research station of the EMBRAPA Amazônia Ocidental, 24 km out of the

Table 1

N (mg kg⁻¹), S (mg kg⁻¹), Ca (Cmol_c kg⁻¹), K (mg kg⁻¹), Mg (Cmol_c kg⁻¹), P (mg kg⁻¹), Al (Cmol_c kg⁻¹) content, and pH (H₂O) of the soil in a depth of 0–20 cm of the monoculture and the enrichment plantation before planting (*n* = 24)^a

Element	Monoculture	Enrichment plantation
N (mg kg ⁻¹)	51.23 a	42.54 b
S (mg kg ⁻¹)	1.62 a	1.60 a
Ca (Cmol _c kg ⁻¹)	0.42 a	0.32 b
P (mg kg ⁻¹)	0.49 a	0.44 a
Mg (Cmol _c kg ⁻¹)	0.10 a	0.07 b
K (mg kg ⁻¹)	3.60 a	2.93 b
Al (Cmol _c kg ⁻¹)	1.68 a	1.57 a
pH (H ₂ O)	4.73 a	5.13 a

^a Values followed by different letters differ significantly between the monoculture and the enrichment plantation at *P* < 0.05 (Fisher's *F*-test).

city of Manaus, 3°8'S, 59°52'W. The area is located at approximately 50 m above sea level with an annual precipitation of about 2500 mm (min. 110 mm (August)/max. 295 mm (February) per month), a mean air temperature of 26.4 °C, and a mean humidity of the air of 87%. According to categorisation, the soil is a poor xanthic Ferralsol (FAO-UNESCO, 1990; Table 1) with a low cation exchange capacity (Zech et al., 1998; Dünisch et al., 1999a; Schroth et al., 2000). The investigations were carried out on a study site which is used for interdisciplinary research projects within the Brazilian–German cooperation program “SHIFT” (Bauch et al., 1999).

The study site was cleared from primary forest in 1980 by slash and burn treatment, as to install a rubber plantation (*Hevea brasiliensis* (H.B.K.) Muell. Arg.). After 2 years, the rubber plantation was abandoned and during the subsequent 10 years covered with a dense diverse secondary vegetation of approximately 78 different species (Preisinger et al., 1994).

For the installation of the monoculture plantation, the secondary vegetation was clear cut without burning in 1991. After 5 months of site preparation, 100 plants (4–6-month-old) of *C. guianensis* were planted with a spacing of 3 m × 3 m in January 1992 in four experimental plots of 25 plants each. Every plant was fertilised with 150 g of superphosphate. The spontaneous vegetation of the plantation was dominated by the cover crops *Pueraria phaseoloides* (Rosed.) Benth and *Homolepis aturensis* (H.B.K.), which were chased and cut by field workers twice a year.

For the enrichment plantation, lines of 30 m $\times$ 2.5 m of the same secondary vegetation were cut in 1991. Between these lines, 5 m of the fallow vegetation remained untouched. In each line, 10 plants (4–6-month-old) of *C. guianensis* were planted with a spacing of 3 m in January 1992. According to the treatment in the monoculture, every plant was fertilised with 150 g of superphosphate. The spontaneous vegetation of the cleared lines was cut by field workers twice a year. Corresponding to the monoculture, the enrichment plantation was installed with four repeats.

Soil analysis carried out in the two plantations before planting indicated low K, Mg, and P contents and high Al contents of the soil (Table 1) of the experimental site. A significant increase of the N, Ca, K, and Mg content of the soil of the monoculture was found after clear cut of the area compared to the enrichment plantation due to the decomposition of the organic material, which remained in the monoculture (Table 1, Dünisch and Schwarz, 2001).

2.2. Nutrient fluxes within the monoculture and the enrichment plantation

The nutrient fluxes within the plantation were calculated for 1-month-intervals. The study was carried out from the start of the plantation until 83 months of growth.

To quantify the nutrient input into the soil, the quantity and the element content of the precipitation, the throughfall, and the stemflow were quantified in 1-month-intervals (sample collection was carried out weekly). The rain collectors ($\varnothing$ 15 cm) were installed in a distance of 50 and 150 cm from the trunk of 12 *Carapa* trees of the monoculture, 12 *Carapa* trees of the enrichment plantation, and 27 trees of the secondary vegetation of the enrichment plantation. Stemflow collectors were installed at four *Carapa* trees of the monoculture, four *Carapa* trees of the enrichment plantation, and nine trees of the secondary vegetation of the enrichment plantation. The K, Mg, and P contents of the solutions were analysed monthly (mixed samples of weekly sample collections) by optical emission spectroscopy with an inductively coupled plasma flame (ICP-OES; Berneike et al., 1985). The nutrient input into the soil was calculated as the product of the amount of precipitation, throughfall and

stemflow, which entered the plantations and the nutrient content of the solutions.

The nutrient input into the soil caused by litterfall and litter decomposition was calculated from weekly litterfall collections (collectors 3 m $\times$ 3 m, four collectors in the monoculture, six in the enrichment plantation) and two litter decomposition experiments carried out in 1995 and 1999 with litter of *Carapa*, of the cover crops *P. phaseoloides* (Rosed.) Benth and *H. aturensis* (H.B.K.), and of mixed litter of 78 species of the secondary vegetation of the enrichment plantation (litterbags 40 cm $\times$ 40 cm, mesh width 1 mm $\times$ 1 mm, four repeats, sample collection after 1, 2, 3, 6, and 12 months). After acid digestion (67% HNO₃), according to Rademacher (1986), the samples were analysed by ICP-OES. The nutrient input into the soil by litter decomposition was calculated as the product of the nutrient content of the litterfall and the mineralisation rate obtained from the decomposition experiments. For the calculation of the nutrient input into the soil by litter decomposition, the mineralisation rate obtained in the litterbag experiment carried out in 1995 was used for the calculation for the years 1992 until 1995 (1–4-year-old plantations), whereas the mineralisation rate obtained from the litterbag experiment carried out in 1999 was used for calculation for the years 1996 until 1998 (5–7-year-old plantations).

The monthly net K, Mg, and P uptake by the vegetation was calculated as the difference of the element content of the vegetation from 1 month to another from the biomass of the trees and the K, Mg, and P analyses of biomass samples (nine tissue fractions, e.g. leaves, bark, stem, fine roots) carried out according to Rademacher (1986). For the quantification of the biomass of the plantations, the survival rate, the breast height diameter, the tree height, the height of the crown, the diameter, and the density of the crown of all *Carapa* trees and of 78 species of the secondary vegetation were monthly monitored. As to prove the significance of the selected dendrometric parameters for the biomass calculation, four *Carapa* trees of the monoculture and the enrichment system with an age of 5, 39, 47, 59, and 83 months were felled and the oven dry biomass (105 °C) of 9–17 plant fractions (e.g. fine roots, main roots, stem xylem, stem phloem, leaves, etc.) was quantified. Corresponding to that the biomass of the secondary vegetation of the enrichment plantation was quantified

at a corresponding area of $10\text{ m} \times 10\text{ m}$ at the beginning of the experiment.

According to a methodical approach of Bredemeier (1987), the leaching of K, Mg, and P out of the soil was quantified from the water balance and the chemical analyses of the soil solution of different soil compartments (0–10, 10–20, 20–60, 60–120 cm depths). The water content of the soil compartments was quantified by weekly tensiometer measurements (T 3 UMS Umweltanalytische Meßsysteme, München) and the pF relationship of the different soil compartments, which was analysed according to Richards (1949). The tensiometers were installed at 5, 15, 35, 65, and 125 cm depths. The element content of the soil solution was quantified in 1-week-intervals at soil depths of 10, 20, 60 and 120 cm. The tensiometers and the suction cups (P80, UMS Umweltanalytische Meßsysteme, München) were installed radially in the four cardinal directions in a distance of 1 and 2 m from the trunk of four *Carapa* trees of the monoculture, four *Carapa* trees of the enrichment plantation, and at six places within the secondary vegetation of the enrichment plantation. The soil solution was sampled with a vacuum of -700 hPa of the suction cups. The nutrient fluxes in the soil were calculated for monthly intervals from the water fluxes from one soil compartment to another and the change of the element content of the soil solution sampled in the different soil compartments. The K, Mg, and P balance of the soil of the two plantations was calculated for monthly intervals for the 83 months of plantation growth as the sum of nutrient input due to wet and dry deposition and litter decomposition minus the sum of nutrient output due to the nutrient uptake of the vegetation and nutrient leaching out of the soil. Water surface runoff and decomposition of fine roots were neglected in this calculation (declination of the study site less than 3%).

2.3. Growth dynamics of *Carapa guianensis* in the monoculture and in the enrichment plantation

The biomass of the two plantations was annually quantified. Based on the breast height diameter, the tree height, the height of the crown, the diameter, and the density of the crown of all *Carapa* trees of the monoculture and the enrichment plantation four *Carapa* trees of the monoculture and the enrichment plantation were selected for excavation and the oven

dry biomass (105°C) of the trees was quantified. The spontaneous vegetation of the cover crops in the monoculture was also annually quantified by destructive harvesting of an area of $4\text{ m} \times 4\text{ m}$. The biomass of the secondary vegetation of the enrichment plantation was quantified by means of destructive harvesting of an area of $10\text{ m} \times 10\text{ m}$ at the beginning of the experiment and dendrometric measurements (breast height diameter, tree height, height of the crown, diameter and density of the crown) carried out annually in four fallow lines of the enrichment plantation according to Dünisch and Schwarz (2001).

The tree height of eight *Carapa* trees of the monoculture and eight *Carapa* trees of the enrichment plantation was quantified in monthly intervals. The significance of the result was cross-checked by tree height measurements of all trees carried out at an age of 5, 39, 47, 59, and 83 months. The total tree biomass of *Carapa* was strongly correlated with the tree height (monoculture: $r^2 = 0.73$, enrichment plantation: $r^2 = 0.87$).

The radius increment of three trees of the monoculture and three trees of the enrichment plantation was quantified in monthly intervals by repeated wounding of the cambium (1–12- and 36–83-month-old plants). The cambium was wounded with a scalpel according to Kuroda and Shimaji (1984). Fixation of the samples was carried out with ethanol (70%) and the radius increment was studied by light microscopy according to Dünisch et al. (1999b). In addition, the radius increment of eight trees each of the monoculture and the enrichment plantation was quantified by dendrometer measurements (four points of measurements per tree) according to Vogel (1994). The correlation coefficient (r^2) between the breast height diameter and the total tree biomass of *Carapa* grown in the monoculture was 0.94, of *Carapa* grown in the enrichment plantation was 0.83.

The total tree biomass was calculated from the regression equations obtained for the relationship of tree height, breast height diameter and total tree biomass of the 1–8-year-old *Carapa* trees (Dünisch, 2001).

2.4. Statistical analyses

As to evaluate the statistical significance of the study the Gauß' error of the investigation (biomass

determination $\times$ nutrient flux determination) was quantified (Dünisch and Schwarz, 2001, in press).

Data were examined by analysis of variance (ANOVA) using age of the plantation and the plantation system (monoculture, enrichment plantation) as treatment factors in a completely randomised design. The significance of the results was tested for $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***; Fisher's F -test). In the tables, values followed by different letters differ significantly between the monoculture and the enrichment plantation at $P < 0.05$ (Fisher's F -test).

3. Results

3.1. K, Mg, P fluxes and balances of the monoculture and the enrichment plantation

The K, Mg, and P balance of the soil (Fig. 5a–c) of the monoculture and the enrichment plantation was calculated for monthly intervals from the nutrient input by rain, throughfall and stemflow (Fig. 1a–c), and by litter decomposition (Fig. 2a–c), from the nutrient output by nutrient uptake of the vegetation

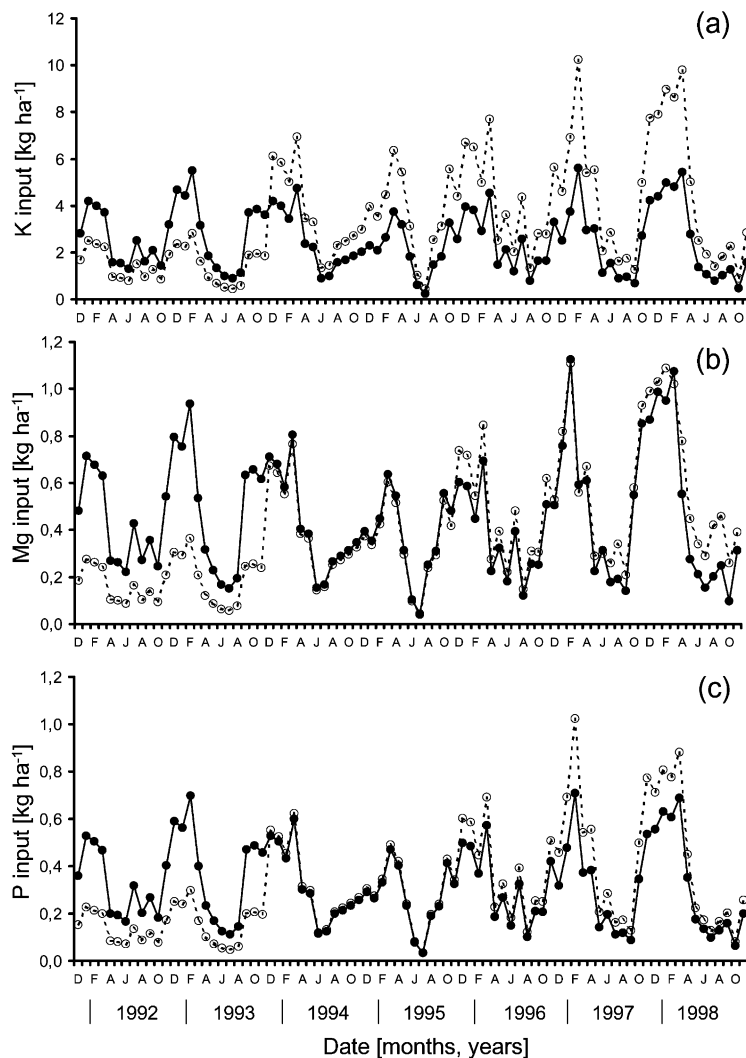


Fig. 1. Monthly (a) K, (b) Mg, and (c) P input (kg ha^{-1}) into the soil by rain, throughfall, and stemflow of the monoculture and the enrichment plantation during the 84 months of experiments (December 1991 until November 1998).

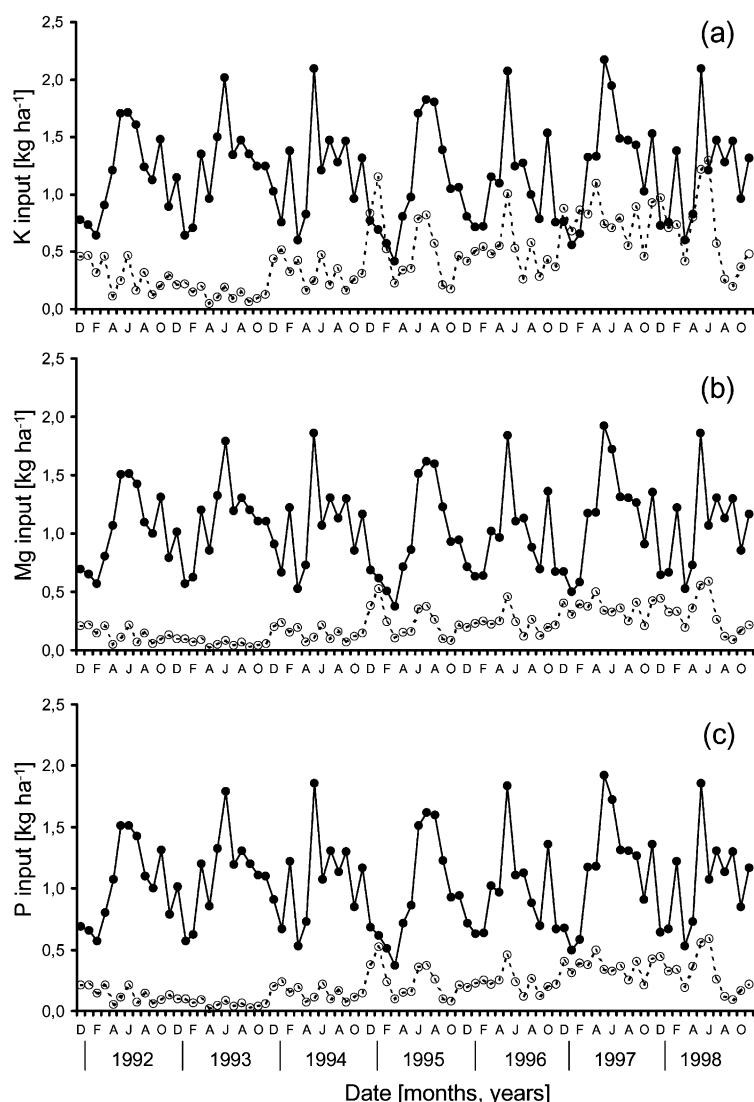


Fig. 2. Monthly (a) K, (b) Mg, and (c) P input (kg ha^{-1}) into the soil by litter decomposition of the monoculture and the enrichment plantation during the 84 months of experiments (December 1991 until November 1998).

(Fig. 4a–c) as well as by leaching of nutrients out of the soil (Fig. 4a–c). The Gauß' error of the calculation of the nutrient fluxes in the plantation varied between 24 and 46%.

The K input into the soil of the plantations by precipitation, throughfall, and stemflow was high compared to the Mg, and P input (Fig. 1a–c). In addition, a strong seasonal variation of the nutrient input was found, which was correlated with the

seasonal variation of the precipitation. Consequently, highest K, Mg, and P input was found during the period from November until May. Due to the high K, Mg, and P content of *Carapa* leaves (Dünisch et al., 1999a), the nutrient input to soil in the monoculture increased with increasing age of the plantation. After 2 years of plantation growth the K input by precipitation and leaching from the crown of the trees in the monoculture exceeded the corresponding data of the

enrichment plantation. The seasonal oscillation of the K input was higher in the monoculture plantation than in the enrichment plantation.

The K and P input into the soil of the two plantations by litterfall and litter decomposition was low (Fig. 2a and c) compared to the K and P input due to precipitation, throughfall and stemflow (Fig. 1a and c), whereas litter decomposition was of main importance for the Mg supply of the plantations (Fig. 2b). Maximum nutrient input into the soil

by litter decomposition was found from May until July, approximately 1 to 2 months after a significant increase of the microbial activity of the soil. As a rule, a higher K, Mg, and P input into the soil by litter decomposition was found in the enrichment plantation compared to the monoculture (Fig. 2a–c). Due to a life cycle of the *Carapa* leaves of 20–25 months, only litter from the cover crops *Pueraria* and *Homolepis* were available for decomposition in the monoculture during the first 2 years of plantation growth.

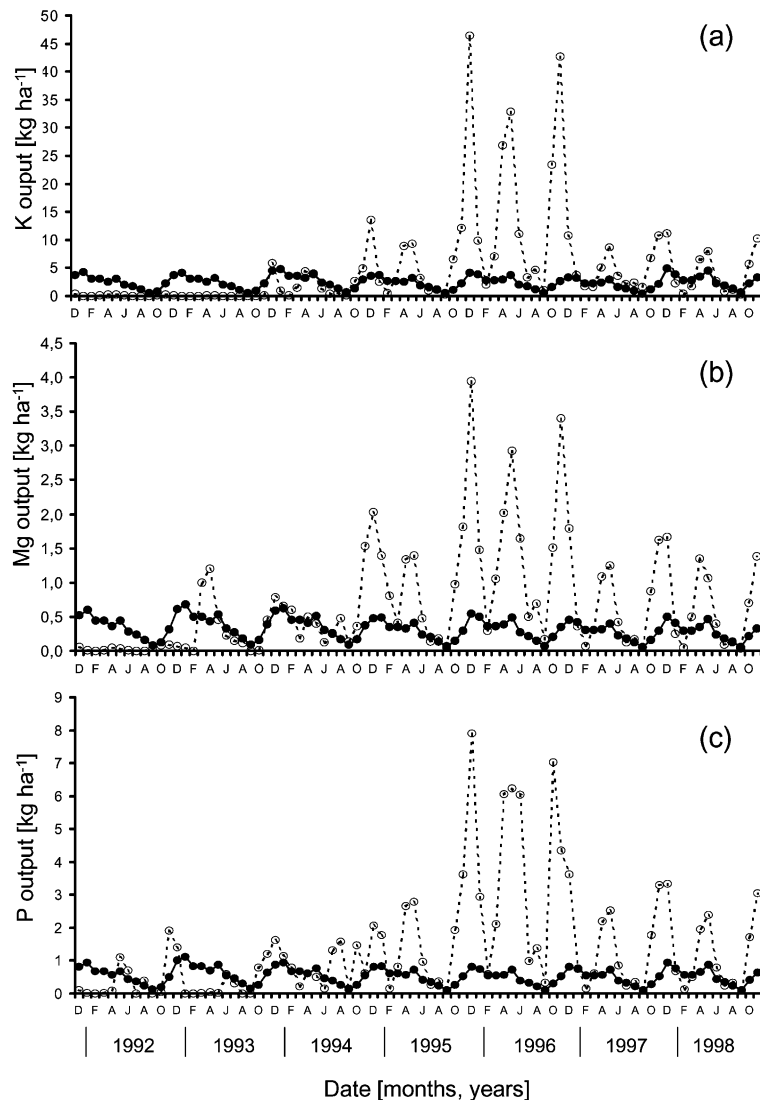


Fig. 3. Monthly (a) K, (b) Mg, and (c) P output (kg ha^{-1}) out of the soil by net element uptake of the vegetation of the monoculture and the enrichment plantation during the 84 months of experiments (December 1991 until November 1998).

net K, Mg, and P uptake of the enrichment plantation was more balanced and intraannual oscillation was less pronounced. In the enrichment plantation, 47–89% of the net K, Mg, and P uptake were caused by nutrient uptake of the spontaneous vegetation of the enrichment lines during the first 3 years, whereas after 7 years more than 95% of the net K, Mg, and P uptake were absorbed by the *Carapa* trees.

During the first 3 years high amounts of K and Mg were leached out of the soil of the monoculture

plantation (Fig. 4a and b), whereas no significant leaching of P was found (Fig. 4c). Maximum K and Mg leaching out of the soil was found during the rainy season from December until May. After 3 years growth K and Mg leaching out of the soil of the monoculture was strongly reduced and only small amounts of K and Mg were leached out of the soil. During the 7 years of experiments no significant leaching of K and Mg out of the soil of the enrichment plantation was found. The water fluxes and the

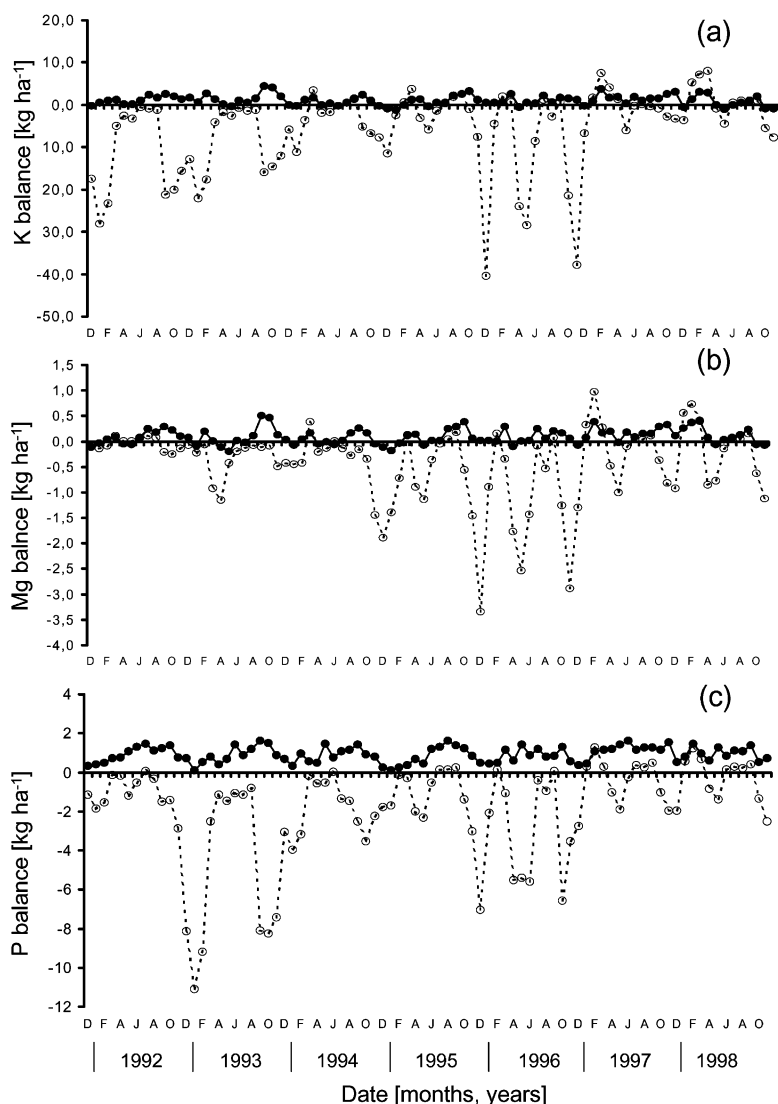


Fig. 5. Monthly (a) K, (b) Mg, and (c) P balance (kg ha^{-1}) of the soil of the monoculture and the enrichment plantation during the 84 months of experiments (December 1991 until November 1998).

chemical composition of the soil solution sampled in the enrichment lines and in the untouched lines of the secondary vegetation were not significantly different.

Based on the K, Mg, and P input and output, nutrient balances were calculated for the monoculture and the enrichment plantation (Fig. 5a–c). During the first 5 years of plantation growth, a significant K, Mg, and P loss of the soil of the monoculture became obvious. Based on this calculation, the reduction of the K stocks of the soil varied between 44 and 114 kg ha⁻¹ per year (Fig. 5a), of the Mg stocks between 5 and 11 kg ha⁻¹ per year (Fig. 5b), and of the P stocks between 0.5 and 9 kg ha⁻¹ per year (Fig. 5c). During the first 3 years, the reduction of the K and Mg contents of the soil was mainly caused by the strong leaching of these two elements out of the soil (Fig. 4a and b and Fig. 5a and b), whereas the negative K and Mg balance in the subsequent years was mainly caused by a surplus of nutrient uptake compared to the K and Mg input into the soil (Fig. 1a and b, Fig. 2a and b, Fig. 5a and b). The reduction of the P stocks of the soil was exclusively caused by the high surplus of P uptake compared to P input into the soil of the monoculture (Fig. 1c, Fig. 2c, Fig. 3c, Fig. 5c). Especially the low P cycling by litter decomposition within the monoculture contributed to the negative P balance of the monoculture plantation (Fig. 2c, Fig. 5c). Maximum monthly values of K, Mg, and P loss out of the soil of the monoculture were correlated with high precipitation and nutrient uptake of the vegetation.

During the 7 years of the experiment the K, Mg, and P balance of the soil of the enrichment plantation was stabilised (Fig. 5a–c), and a low surplus of Mg input compared to nutrient output was detected (Fig. 5b). In addition, the seasonal variation of the K, Mg, and P balance was less in the enrichment plantation compared to the monoculture.

3.2. Growth of *Carapa* under monoculture and enrichment plantation conditions

The biomass production of the *Carapa* monoculture strongly increased during the first 4 years of growth (Fig. 6a and b). Due to the strong competition with the *Carapa* trees, the cover crops disappeared already after 3 years of growth, and as a consequence, the litter

layer of the soil exclusively consisted of the slow decomposing litter of *Carapa* (compare Fig. 2a–c). After 5 years growth, the biomass production of the *Carapa* monoculture was strongly reduced. Due to the moderate silvicultural treatment carried out in the enrichment plantation, a biomass stock of approximately 80 t ha⁻¹ of secondary vegetation remained in the area before planting. During the period of experiments, the biomass stock of the enrichment plantation was higher compared to the monoculture. In contrast to the monoculture, more than 90% of the biomass of the enrichment plantation were located in the biomass of the untouched fallow vegetation during the first 4 years, but after 5 years, a significant increase of the biomass was found, which was mainly caused by a strong biomass production of the *Carapa* trees. After 7 years, approximately 23 t ha⁻¹ of the biomass of the enrichment plantation were located in the *Carapa* trees, whereas the biomass of the fallow vegetation was slightly reduced. After 7 years, the curves of biomass production still indicated steady biomass production in the enrichment plantation, whereas the biomass production strongly decreased in the monoculture (Fig. 6a and b).

After 7 years of growth, a survival rate of the planted *Carapa* trees of 83 and 80% was found in the monoculture and in the enrichment plantation, respectively (Table 2). In addition, no significant differences in height increment of the trees were found in the two plantations during the first 7 years of growth, whereas after 8 years the mean tree height of *Carapa* grown in the enrichment plantation exceeded the mean tree height of *Carapa* grown in the monoculture (Fig. 6a). Intraannual investigations on the course of the height increment showed no distinct periodicity in height increment during the first 3 years of growth (Fig. 6a). In the subsequent years, maximum values of height increment were found in January and February. The breast height diameter and the crown diameter of the trees grown in the enrichment plantation were significantly reduced compared to the monoculture plantation (Table 2). Although the total tree biomass of *Carapa* grown in the monoculture was higher compared to the trees grown in the enrichment plantation, the bole production of *Carapa* grown in the enrichment plantation was higher compared to *Carapa* grown in the monoculture (Table 2). With regard to timber production, the

experimental area (Stark, 1970; Sanchez, 1976; Zech et al., 1998). With regard to the installation of sustainable plantations for wood production in this region, the stabilisation of the K, Mg, and P stocks of the soil is of main importance (Klinge, 1976; Jordan, 1982; Sanchez et al., 1982; Szott and Palm, 1996).

The results of our study show that the history of the study site and the site preparation are of main importance for the conservation of the nutrient stocks of plantations on “terra firme” sites. Still after 7 years, vegetation clearing for the installation of the monoculture plantation predominately influenced the nutrient fluxes and the nutrient pools of the site (Klinge, 1976; Jordan, 1982). After 7 years the loss of nutrient pools by vegetation clearing exceeded the losses by nutrient leaching out of the soil, which shows the significance of appropriate site preparation techniques for the nutrient supply in plantations (Hölscher et al., 1997).

Although not all nutrient fluxes (e.g. mortality and decomposition of fine roots) in the plantation were considered in our study the data indicate that during the first years after the installation of the monoculture the nutrient output out of the soil is higher than the nutrient input into the soil, whereas the 10-year-old fallow vegetation, which remained untouched in the enrichment plantation favours the stabilisation of the nutrient stocks. Especially the strong reduction of the K and Mg leaching out of the soil of the enrichment plantation and the better external nutrient cycling due to litterfall and litter decomposition compared to the monoculture emphasises the ecological function of the secondary vegetation for the recuperation of cleared primary forests in this area (Uhl et al., 1981; Cuevas and Medina, 1986). A comparison of the nutrient input into the soil by wet and dry deposition and by litter decomposition elucidated the importance of the secondary vegetation, especially for the Mg supply of the soil. Due to the importance of Mg for the photosynthesis of the trees and several enzymatic activities of the trees (Küppers et al., 1985), a strong impact of the reduced Mg cycling in the monoculture on the wood production of the *Carapa* trees is likely.

Due to the imbalance of K and Mg input and output caused by high element leaching out of the soil during the first 3 years of growth and the low P stocks of the

soil, an insufficient K, Mg and P supply of the planted *Carapa* trees might be responsible for the decrease of the biomass increment after 6 years in the monoculture. In agreement to soil analyses carried out by Schroth et al. (2000) on the study site, this result gives evidence that after 5 to 6 years, fertilisation with K, Mg, and P is an urgent need for steady tree growth of *Carapa* in the monoculture plantation. The intraannual study on nutrient input and nutrient output indicated a high nutrient demand of the *Carapa* trees especially during the rainy season from December until May. As to avoid loss of fertilisers by leaching, fertilisation should preferably be carried out during the drier season. Due to the low nutrient uptake of the young plants, fertilisation is not very promising during the first 3 years of growth. Therefore, higher biomass stocks (preferably with different species; Lieberei and Gasparotto, 1998) are recommended at the initial phase of this plantation.

Although the study on the K, Mg, and P fluxes and balances of the enrichment plantation compared to a traditional monoculture plantation revealed results for sustainable nutrient supply of the planted *Carapa* trees, the economic acceptance of the plantation depends on productivity expressed in terms of biomass and timber production and wood quality (Zobel and Buijtenen van, 1989; Bauch and Dünisch, 2000). For enrichment plantations, the competition (light, water, mineral elements) with the secondary vegetation often is a serious problem for the cultivation of trees for wood production in enrichment plantations (Lamprecht, 1986). This study carried out with *Carapa* indicated a steady biomass production of *Carapa* in the enrichment plantation after 8 years of growth, whereas the biomass increment of *Carapa* already decreased in the monoculture after 5 years of growth. The biomass of trees grown in the enrichment plantation was slightly reduced compared to the biomass of trees grown in the monoculture. Nevertheless, due to the strong apical dominance during the first years and a subsequent increase in cambial growth of the stem of *Carapa* grown in the enrichment plantation, a higher wood production was found compared to the trees grown in the monoculture. This indicates a good adaptation of *Carapa* to the site conditions and the competition in the enrichment plantation due to its wide ecological amplitude (Pennington et al., 1981). In addition, a better wood

quality of *Carapa* grown in the enrichment plantation compared to *Carapa* grown in the monoculture could be expected due to the apical dominance and the more homogeneous growth dynamics in wood formation of the trees grown in the enrichment plantation (Dünisch et al., 1999b; Bauch and Dünisch, 2000). Although the number of planted *Carapa* trees was low per hectare in the enrichment plantation, already after 7 years the enrichment plantation reaches 61% of the productivity (annual wood production per hectare) of the monoculture.

From these results, it was concluded that enrichment plantations are an appropriate tool for the stabilisation of the nutrient stocks of the poor soils of “terra firme” sites of the central Amazon. Due to the strong competitiveness and the ecological adaptation of *C. guianensis* Aubl., the cultivation of this species in enrichment plantations is also promising from an economic point of view. For the application of the results obtained from the present experiment and an optimisation of the enrichment plantation, a calculation of profits and costs is recommended. The study was carried out during the initial phase of plantation growth. As to obtain information on the sustainability of tree growth of *Carapa* in the plantations the study has to be extended to older plantations.

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