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Environment-tree growth relationships of plantation grown tropical tree species as a basis for sustainable timber production in mixed culture systems in Central Amazonia

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ABSTRACT

This comparative study on environment-tree growth relationships of the high quality native tree species *Swietenia macrophylla* King and *Carapa guianensis* Aubl. is part of the development of sustainable landuse systems on „terra firme“ sites of the Central Amazon within the Brazilian-German research cooperation SHIFT (Studies on Human Impact on Forests and Floodplains in the Tropics). As to get information on the site demands and the growth characteristics of plantation grown *Swietenia macrophylla* and *Carapa guianensis* the significance of the water and K supply of the soil for the cambial growth dynamics of the trees was studied in two different plantation systems of *Swietenia macrophylla* and *Carapa guianensis*: (1) monoculture system and (2) an enrichment system (both established in 1992 at the experimental site of the EMBRAPA Amazônia Ocidental in Manaus). The water balance of the plantations was quantified by evaporation and transpiration/xylem flux measurements as well as the calculation of the water run-through in the spoil (CI-method). The K supply of the trees was investigated by quantified input (precipitation, throughfall, stemflow, litterfall) and output data (K uptake of the vegetation, leaching out of the soil). The cambial growth dynamics of the trees was dated in one-month-intervals by the pinning method during the period April 1995 until December 1996).

A reduced soil water content with a suction force in the upper soil layer (depth 20 cm) of 500 to 900 hPa was found from August until November in both plantation systems. High evaporation and water run-through caused short periods with low soil water contents (300 to 400 hPa) even during the wet season in monoculture systems. A cambial dormancy or a reduced rate of cambial cell divisions of *Swietenia* was found during the drier season from August to December whereas the cambial growth dynamics of *Carapa* was not correlated with the annual course of the soil water content. K cycling was improved in the enrichment system compared to the monoculture system, whereas the K supply of the soil was reduced. The reduced xylem production of *Swietenia* in the enrichment system compared to the monoculture system was correlated with the low K content of the soil in this system. From these results it was concluded that *Carapa* is more competitive for sustainable growth on this site than *Swietenia*.

RESUMO

Este estudo comparativo sobre a relação ambiente-crescimento de espécies nativas produtoras de madeira de alta qualidade de *Swietenia macrophylla* King e *Carapa guianensis* Aubl., faz parte do desenvolvimento de sistemas sustentáveis de uso da terra, em áreas de „terra firme“ na Amazônia Central, dentro do programa de cooperação científica Brasil/Alemanha – SHIFT (Studies on Human Impact on Forest on Floodplains in the Tropics). Assim, as informações obtidas sobre as demandas do sítio e as características de crescimento das plantações de *Swietenia macrophylla* e *Carapa guianensis*, a significância da água e do solo para a dinâmica de crescimento cambial das árvores, foram estudadas em dois sistemas diferentes de plantação de *Swietenia macrophylla* e de *Carapa guianensis*: (1) em monocultivo e (2) na capoeira enriquecida (ambos estabelecidos em 1992 no campo experimental do EMBRAPA Amazônia Ocidental, Manaus).

O balanço de água das plantações foi quantificado pela evaporação, medições da relação entre a transpiração e o fluxo no xilema, bem como pelo cálculo do fluxo de água no solo (Método – CI).

O suprimento de K para as árvores foi investigado pela quantificação das entradas nos sistemas de plantio (precipitação, lixiviação de nutrientes da copa para o solo, pelo escorrimento pelo tronco e da liteira) e dados de saída. (absorção de K pela vegetação e lixiviação pelo solo). A dinâmica de crescimento cambial das árvores foi datado em intervalos mensais, com auxílio do método de ferida do câmbio, durante o período de Abril de 1995 a Dezembro de 1996.

Uma baixa quantidade de água disponível de água no solo, com uma força de sucção (tensão) na camada superficial do solo (profundidade de 20 cm) de 500 a 900 hPa foi encontrado de Agosto a Novembro em ambos sistemas de plantio. Alta evaporação e a água lixiviada no solo causaram, quequenos períodos com baixo conteúdo de água no solo (300 a 400 hPa) sempre na estação seca, no sistema de monocultivo. Uma dormência cambial ou uma reduzida taxa de divisão celular do câmbio de *Swietenia* foi encontrada durante a estação seca, de Agosto a Dezembro, enquanto que, a dinâmica de crescimento cambial de *Carapa* não foi correlacionada à variação sazonal da disponibilidade de água no solo. A ciclagem de K foi melhor no sistema de enriquecimento, em comparação monocultivo, entretanto, o suprimento de K do solo foi reduzido. A reduzida produção do xilema de *Swietenia* no sistema de enriquecimento, comparado com o monocultivo foi correlacionado com o baixo conteúdo de K no solo neste sistema. A partir desses resultados, conclui-se que a *Carapa* é mais competitiva para o crescimento sustentável nestes sítios do que a *Swietenia*.

ZUSAMMENFASSUNG

Im Rahmen der Brasilianisch-Deutschen Kooperation SHIFT (Studies of Human Impact on Forests and Floodplains in the Tropics) wurde für *Swietenia macrophylla* King. und *Carapa guianensis* Aubl. die Wechselbeziehung exogener Einflüsse und Wachstum studiert, um die Eignung dieser Baumarten für nachhaltige Wirtschaftssysteme auf der Terra Firme in Zentralamazonien zu prüfen. Insbesondere wurden Anforderungen an den Standort dieser beiden Baumarten, wie z. B. Wasser- und K-Versorgung in Bezug auf die Wachstumsdynamik berücksichtigt. Für beide Baumarten wurden zwei Pflanzsysteme ausgewählt: (1) Ein Monokultursystem und (2) ein Anreicherungs-system (beide 1992 als Versuchsflächen von EMBRAPA Amazônia Ocidental, Manaus, angelegt).

Der Wasserhaushalt der Plantagen wurde durch die Evaporation und die Transpiration bzw. die Xylemflußmessungen sowie durch den Wasseraustrag im Boden (CI-Methode) bestimmt. Die K-Versorgung der Bäume wurde Input- (Niederschlag, Bodenniederschlag, Stammfluß, Laubfall) und Output-Messungen (K-Aufnahme der Vegetation, Leaching) ermittelt. Die Wachstumsdynamik am Kambium wurde anhand der Pinning-Methode von April 1995 bis Dezember 1996 in monatlichen Abständen registriert.

In beiden Plantagensystemen wurde von August bis November ein reduzierter Bodenwassergehalt mit einer Saugspannung in der oberen Bodenschicht (ca. 20 cm Tiefe) von 500 bis 900 hPa bestimmt. Im Monokultursystem bewirkte eine hohe Evaporation und der Wasseraustrag kurzzeitig sogar in der Regenzeit einen niedrigen Bodenwassergehalt (300 bis 400 hPa). Eine Wachstumspause bzw. eine sehr reduzierte kambiale Zellteilung erfolgte bei *Swietenia* während der trockeneren Zeit von August bis Dezember, während für *Carapa* keine Korrelation mit dem Bodenwassergehalt festgestellt wurde. Das K-Recycling war im Anreicherungssystem im Vergleich zur Monokultur verbessert, hingegen war der K-Vorrat im Boden entsprechend rückläufig. Die verminderte Holzproduktion von *Swietenia* in der Anreicherungskultur im Vergleich zur Monokultur dürfte mit dem geringen K-Vorrat im entsprechenden Boden erklärbar sein. Es wird allgemein geschlossen, daß *Carapa* für ein nachhaltiges Wachstum auf den gewählten Standorten wettbewerbsfähiger als *Swietenia* sein dürfte.

INTRODUCTION

In urban areas of Central Amazonia an increasing demand on agricultural products and wood is obvious (Benchimol 1996). The main reason is the distinct trend of population growth in cities. Traditional systems for land use and monocultures around the cities cannot guarantee a sustainable production and cannot sufficiently supply the population with food and wood (Fearnside 1993, Hannon and Betalha 1995). The consequence is the increasing demand for new land, which leads to extensions into the tropical forests (Sanchez et al. 1982, Fearnside 1995, Fernandes et al. 1997).

Particularly the increasing demand for wood is exclusively available from primary forests, which frequently leads to exploitation of high quality species (Dahms 1989). The negative development is as a rule associated with serious negative affects on the ecosystem „tropical forest“ (Lambrecht 1986, Fearnside 1993, Bruenig 1996). The restricted availability of special high quality timber for Amazonia may even lead to the import of wood to some extent (Benchimol 1996).

To counteract this tendency EMBRAPA Amazônia Ocidental in Manaus develops sustainable land use systems, accompanied since 1992 with a Brazilian-German cooperation (SHIFT). One main aspect is the recultivation of degraded areas (Autorenkollektiv 1995). The main aim are polycultures with agroforestry tendencies. That means, that agricultural oriented systems should to some extent include native tree species for high valuable wood production (Whitmore 1993).

The knowledge about the growth and the site demand of important commercial native tree species of the Central Amazon is still restricted. Therefore it is important to study the dynamics of growth in combination with the site conditions. From such investigations

conclusions for the management of mixed plantations can be drawn with regard to an optimum in productivity and sustainability.

Therefore this investigation has for its main aim the study of the influence of exogenous parameters on the growth and wood formation of the two high quality tree species *Swietenia macrophylla* King and *Carapa guianensis* Aubl. of the Central Amazon. On account of the specific situation of degraded areas, special significance is donated to the water and the nutrient element supply of the trees (comp. Klinge 1976, Sanchez et al. 1982, Lambrecht 1986, Schmidt 1996).

The concept of the project ENV 42 is part of the interdisciplinary research program SHIFT (Studies on Human Impact on Forests and Floodplains in the Tropics) at the EMBRAPA Amazônia Ocidental in Manaus. There are tight links to ENV 23 (comp. Schmidt 1996, Preisinger 1996), ENV 45 (comp. Schroth 1996) and ENV 52 (comp. Beck et al. 1998).

MATERIAL AND METHODS

In this study the influence of the water and K supply on growth and wood formation of plantation grown *Swietenia macrophylla* and *Carapa guianensis* is investigated. As to study the influence of the plantation management on important site factors such as (1) the water and (2) the K supply and with that on (3) wood formation of the trees, monoculture systems of *Swietenia macrophylla* and *Carapa guianensis* (system I) are compared with a corresponding enrichment system (system III). The experimental plots are located at the EMBRAPA Amazônia Ocidental, Manaus 3°8'S, 59°52'W.

System I (established January 1992):

- Former monoculture of *Hevea brasiliensis* (H.B.K.) Muell.Arg., clear cut in 1991
- Monoculture systems of 20 selected tree species with 4 repeats and 25 plants per plot
- Spacing 3 x 3m
- Fertilization 1992: 150g superphosphate per tree
- Spontaneous vegetation is suppressed by cover crops *Pueraria phaseoloides* (Rosed.) Benth and *Homolepis aturensis* (H.B.K.) Chase and cutting by field workers.

System III (established January 1992):

- Former monoculture of *Hevea brasiliensis*
Enrichment of a 25 years old secondary vegetation with 10 species.
10 plants per species, 4 repeatings
- Spacing 3 x 6m
- Fertilization 1992: 150g superphosphate per tree
Spontaneous vegetation was not cut or suppressed since 25 years; Dense vegetation with 76 genera out of 39 families.

(1) The suction force of the soil was monitored by tensiometer measurements in a soil depth of 10, 20 and 60cm. The air temperature, the air humidity, the precipitation, the throughfall and the stem flow are quantified. The transpiration of the trees was quantified by calibrated xylem flux measurements (Granier 1985, Erbreich 1997).

(2) The K supply of the soil solution was quantified in one week intervals in a depth of 10, 20 and 60cm. The K content of the soil (total K content and Ake) was quantified annually from 1995 until 1997. The element input via litterfall, throughfall and stem flow was also

determined in monthly intervals. Decomposition rates were calculated from litter bag experiments. The element content of the plant tissues was studied by bulk analyses (ICP-OES, comp. Berneicke et al. 1985) as well as by subcellular element analyses (TEM-EDXS, Dünisch et al. 1998).

(3) The structural dynamics in wood formation expressed in terms of monthly increment rates was quantified by the pin marker technique (comp. Mariaux 1969, Kuroda 1986) for 3 trees of each plot.

RESULTS

1. The water supply of plantation grown *Swietenia macrophylla* and *Carapa guianensis*

As to quantify differences in water supply between the wet period from December until June and the drier period from July until November water fluxes for the two plantation systems I and III were studied (comp. also Morais et al. 1998, Schroth et al. 1998).

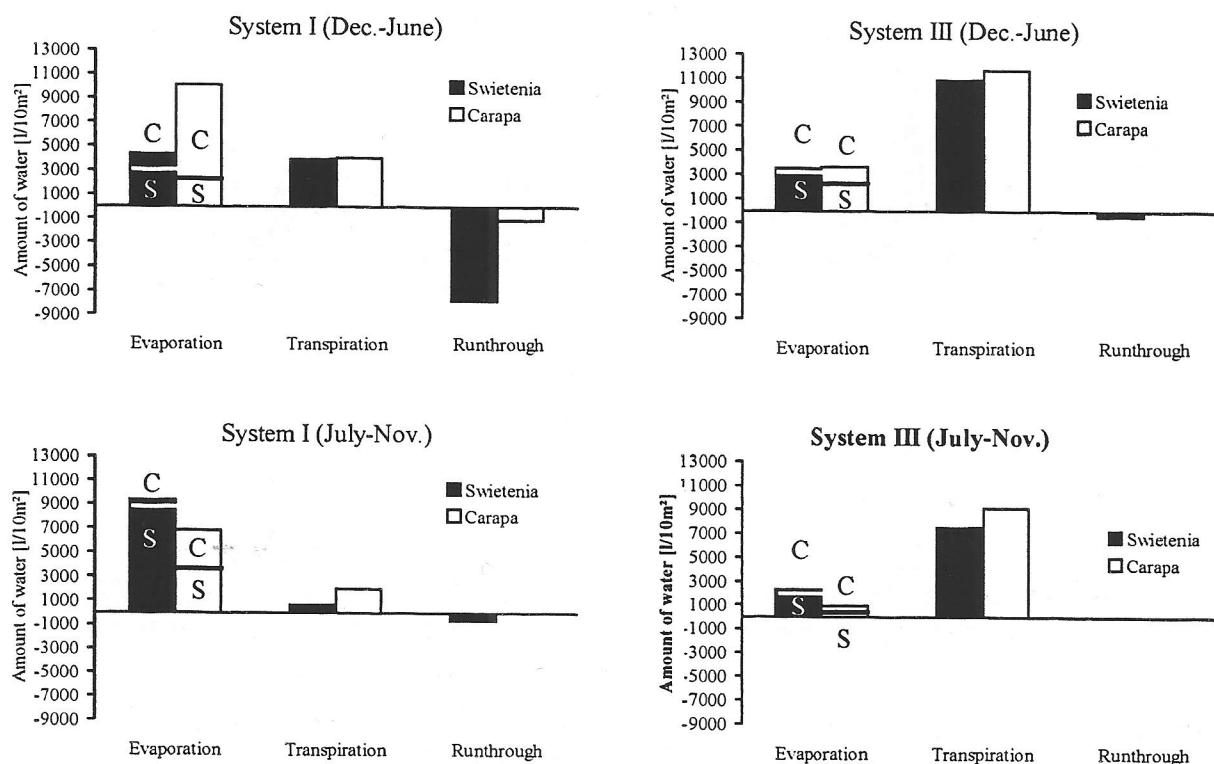


Figure 1: Evaporation of the soil (S) and from the crown (C), transpiration and water runthrough [$l/10m^2$] of plantation grown *Swietenia macrophylla* and *Carapa guianensis* for the wet period from December 1996 until June 1997 and the dry season from July until November 1997, plantation systems I and III.

In *Swietenia* monocultures soil evaporation, in *Carapa* monocultures evaporation from the crown are of main importance for the water output out of the plantation (Figure 1). Furthermore in *Swietenia* monocultures a high amount of water run-through in the soil was quantified, which indicates a high leaching of mineral elements in this system (comp. also Figure 3 and Figure 4). The high amount of water run-through in the *Swietenia* monoculture compared to *Carapa* is mainly caused by the reduced transpiration of *Swietenia* trees compared to *Carapa* especially in June, July and November.

In contrast to that 40 to 70% of the water output out of the plantation system III is caused by transpiration, whereas soil evaporation and run-through are strongly reduced (Figure 1). A comparison of the transpiration of the monocultures and the enrichment system during the drier season from July until November indicates that the trees and shrubs of the secondary vegetation are more adapted to drier periods compared to the planted timber trees, which is indicated by high transpiration rates in system III even from July until November. This is confirmed by further studies on the plant-water relationships of the secondary vegetation carried out in cooperation with the SHIFT project ENV 23 (comp. Morais et al. 1998).

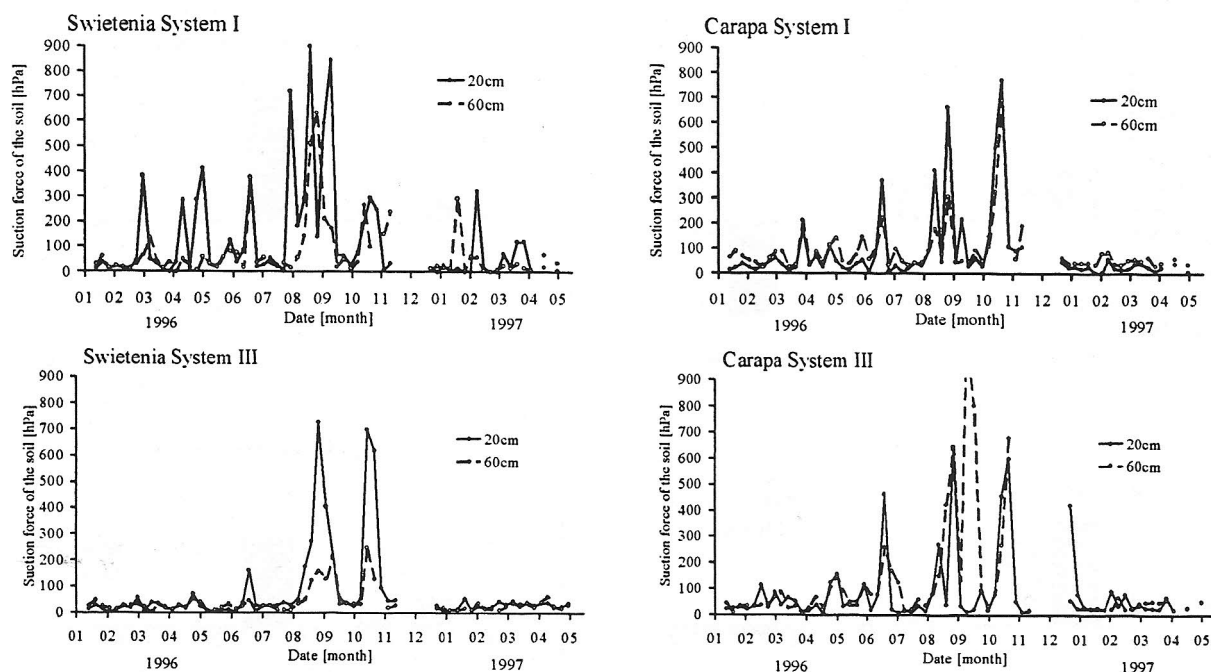


Figure 2: Suction force of the soil [hPa] in a soil depth of 20 and 60cm of plantation grown *Swietenia macrophylla* and *Carapa guianensis* for the period January 1996 until May 1997.

These findings were confirmed by tensiometer measurements, which indicated a reduced water supply of the soil in all plantation systems from August until November caused by the significant reduction of the precipitation during this period (Figure 2).

A comparison of the suction force of the soil between the monoculture system and the enrichment system confirms that the secondary vegetation of the enrichment system serves as a buffer against strong oscillation of the soil water content, especially in the wet period from

December until June (Figure 2). Although the monthly precipitation of this period varies between 120 and 470mm, short periods with a reduced soil water supply with values up to a critical level of 400 hPa were detected in monocultures, particularly in the upper soil layer of *Swietenia* monocultures. In contrast to that the soil water content of the plantation system III is more or less stabilized during this period. This indicates that short water stress might occur in 5-year-old monocultures even during the wet season from December until June.

2. The K supply of plantation grown *Swietenia macrophylla* and *Carapa guianensis*

The K supply of the trees was studied in terms of quantified input and output data within the plantation systems since March 1995. From these investigations it becomes obvious that in the 4-year-old monoculture system the K input and K output is not balanced (Figure 3), which is mainly caused by high K leaching out of the soil in *Swietenia* plantations and high K uptake rates in *Carapa* plantations. This indicates a better absorbency capacity for mineral elements of *Carapa guianensis* compared to *Swietenia macrophylla*.

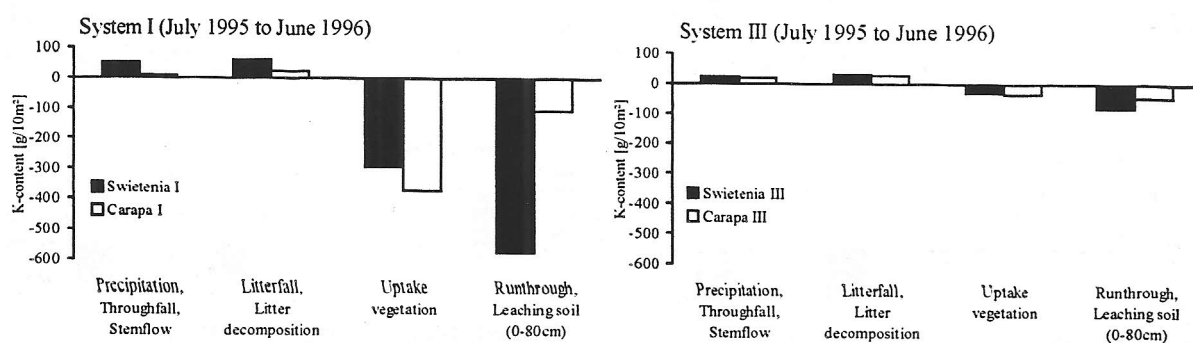


Figure 3: K input (precipitation, throughfall, stemflow, litterfall/litter decomposition) and K output (uptake of the vegetation, leaching) of the soil [g/10m²] in the plantation systems I and III during the period July 1995 until June 1996.

In contrast to that in the enrichment system (system III) the K input is in the same order of magnitude as the K output (Figure 3), which indicates a more stabilized K balance in this plantation system compared to the monoculture system (system I).

Consequently to that during the first years of the plantation a reduction of the K stock of the soil was observed in the plantation system I (Figure 4). Under monoculture conditions the K stock of the soil is strongly reduced in 1996 compared to 1995, whereas no corresponding increase of the K content located in the biomass could be observed. This is explained by the high leaching of K out of the soil in the 4-year-old monoculture system. On the other hand no significant alteration of the K stock of the soil was found in the enrichment system in 1996 compared to 1995.

Nevertheless the total K content of the soil of the 4 and 5-year-old monoculture system is higher compared to the 29 and 30-year-old secondary vegetation of the enrichment system

(Figure 4), which indicates a strong competition for K uptake between the spontaneous vegetation and the planted trees in the plantation system III.

The K content located in the litter layer increased from 1995 to 1996 in the monoculture system, whereas only small amounts of K are located in the litter layer of the plantation system III (Figure 4). This is caused by an improved litter decomposition in the enrichment system compared to the monoculture, which also indicates that even after 5 years the K supply of the monoculture system is not stabilized (comp. also SHIFT project ENV 52).

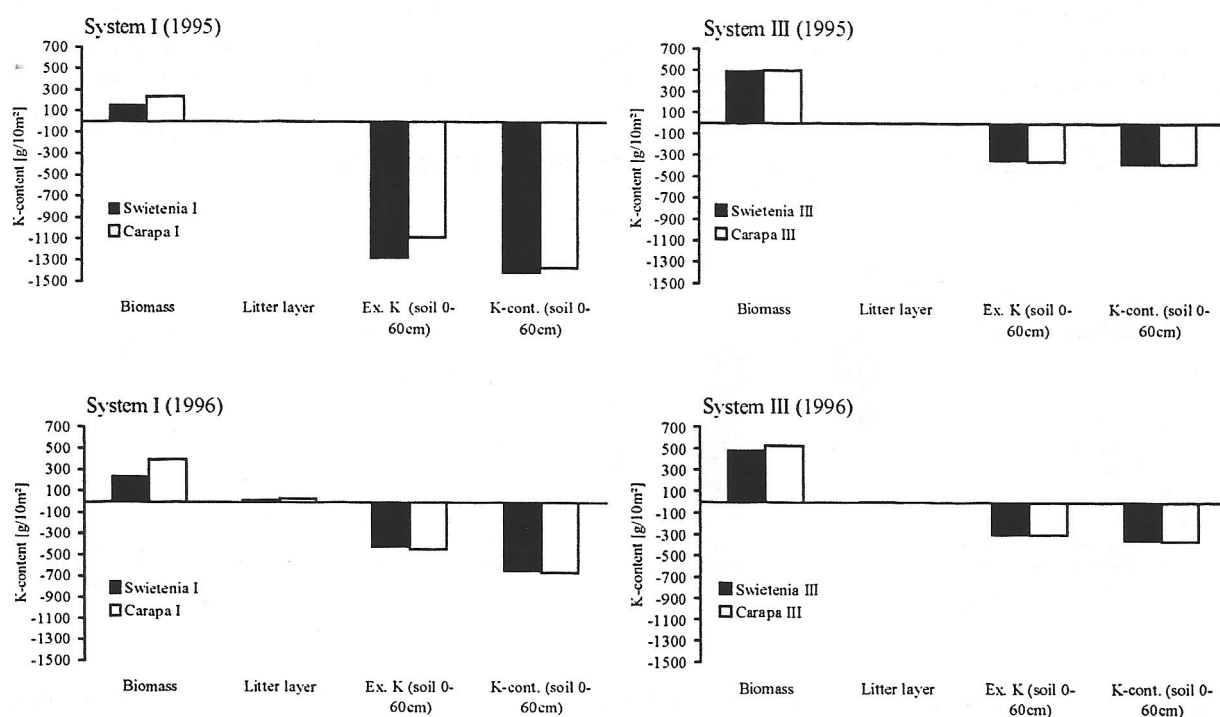


Figure 4: K stocks [g/10m²] located in the biomass, the litter layer and the soil (exchangeable K, total K content) of the plantation systems I and III in December 1995 and December 1996.

3. The cambial growth dynamics of plantation grown *Swietenia macrophylla* and *Carapa guianensis*

As to study the significance of the water and K supply for the cambial growth dynamics of the trees the monthly increment of the trees was compared with the water and K supply within the plantation systems.

The quantification of the water supply in the plantation systems I and III showed that the seasonal variation of the precipitation causes a strong reduction of the soil water supply from August until December. The intraannual cambial growth dynamics of *Swietenia*, expressed in terms of monthly increment (Figure 5) shows a corresponding decrease of the rate of cambial cell divisions or even a cambial dormancy during this period.

In contrast to that no correlation was found between the reduced soil water content from August to December and the cambial growth periodicity of plantation grown *Carapa* (Figure 5). This indicates that wood formation of *Carapa* is less influenced by drier periods than wood formation of *Swietenia*.

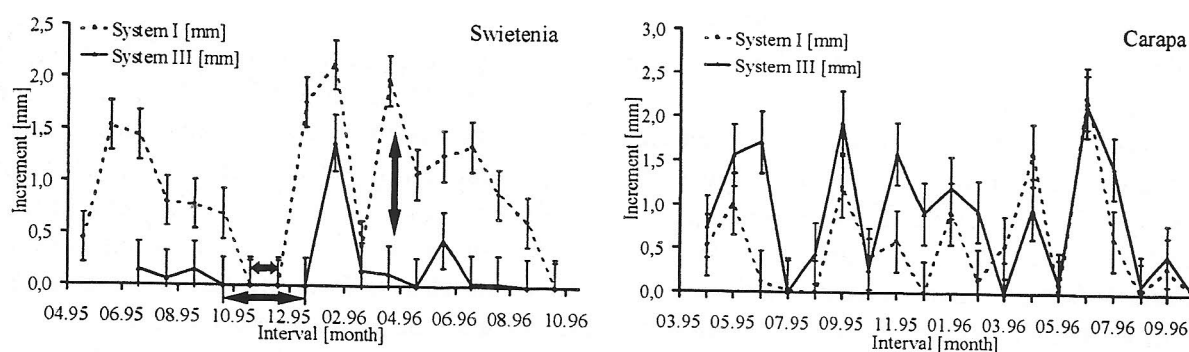


Figure 5: Monthly increment [mm] of *Swietenia macrophylla* and *Carapa guianensis* during the period April 1995 until October 1996 in the plantation systems I and III.

Furthermore a reduced xylem production of *Swietenia* grown in the plantation system III compared to system I is of main interest (Figure 5), which is not explained by differences in the soil water supply between the plantation systems I and III. The reduced xylem formation of *Swietenia* grown in the plantation system III compared to the plantation system I is caused by a reduced rate of periclinal cell divisions during the growing season and a reduced period of cambial cell divisions. The period of cambial cell divisions of *Swietenia* grown in system I lasts from December until October, whereas cambial cell divisions of *Swietenia* grown in system III only were observed from January until September. The reduced xylem production of *Swietenia* in system III is correlated with the reduced K content of the soil of the 4-year-old plantation system III compared to system I (comp. Figure 4). This is a hint for a high sensitivity of the wood formation of *Swietenia* to low K supply. This is caused by the high specific K demand of this tree species.

In contrast to that no significant correlation was found between the K content of the soil and the monthly increment of *Carapa* grown in the plantation systems I and III indicating a lower sensitivity of the cambial growth dynamics of *Carapa* to a reduced K supply as well.

DISCUSSION AND CONCLUSION

The investigation of environment-tree growth relationships of plantation grown *Swietenia macrophylla* and *Carapa guianensis* showed that the site factors water supply and K supply are of main importance for sustainable growth in plantation systems on degraded land areas of the Central Amazon.

The water balance of areas without the dense and diverse vegetation of primary forests (comp. Preisinger et al. 1994) is completely different from natural site conditions of the tropical rain forest (comp. Klinge 1976, Whitmore 1993). Due to short changes between

water saturated soil conditions with high water run-through (comp. Schroth et al. 1998) and periods with high evaporation and transpiration rates (comp. Kramer 1985, Lyr et al. 1992, Müller 1998) in plantation systems, short periods with plant water stress might occur even during the rainy season. This might cause significant alterations of the cambial growth dynamics of plantation grown trees compared to primary growth due to the significance of the water supply for wood formation (comp. Zimmermann 1983, Fritts et al. 1991, Kozlowski et al. 1991, Dünisch et al. 1995, Larson 1995).

The element supply with P and K is a growth limiting factor in many areas of the Central Amazon (Klinge 1976, Sanchez 1982, Lambrecht 1986, Bruenig 1997). The role of the vegetation in primary forests for the element cycling is emphasized in many field studies (Jordan 1982, Whitmore 1993, Fernandes et al. 1997). Especially for the very mobile element K a high absorbency capacity of the vegetation is of main importance as to avoid element loss due to K leaching out of the soil, especially during the first years of plantations (comp. Schmidt 1996) as it was especially shown for a monoculture system in this study. A balanced K input and K output of the plantation systems is also of main importance due to the significance of K for the cambial cell development of trees (comp. Kleinig and Sitte 1992, Dünisch et al. 1998).

The comparison of two different plantation systems (monoculture system, enrichment system) of the same age in this study showed, that the water supply and the K supply of the trees can be stabilized by management practices (comp. Lambrecht 1986, Bruenig 1997). This confirmed that flux measurements of site factors such as the water and mineral element supply are the basis for the evaluation of the sustainability of tree growth in plantation systems (comp. Beck et al. 1998, Zech et al. 1998).

The study also showed that the cambial growth dynamics of *Swietenia macrophylla* is strongly influenced by the soil water and mineral element supply of the soil (comp. Coster 1927), whereas wood formation of *Carapa guianensis* reacts less sensitive to changes in the water and K supply (comp. Breitspecher and Bethel 1990). From these findings we conclude that *Carapa guianensis* is more competitive for sustainable growth on this site compared to *Swietenia macrophylla*.

This indicates that the growth dynamics of tree species with a similar wood characteristic (*Swietenia macrophylla*/ *Carapa guianensis*) can significantly differ (comp. Gottwald 1961, Dahms 1989) and the selection of suitable tree species for high quality timber production in plantation systems is of main importance for the sustainability of the plantation. Therefore investigations on the structural dynamics of plantation grown trees (comp. Bendtsen 1978, Zobel 1985, Harzmann and Müller 1987, Bhat et al. 1989, Schuster 1996) have to be carried out in combination with studies on the growth dynamics of the trees (Vetter 1995, Worbes 1995) as to judge the sustainability of plantation systems from the ecological and economic point of view.

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