Biomass production and mineral element content of *Swietenia macrophylla* King in the juvenile phase under plantation conditions in Central Amazonia

P. Schmidt,[1] *R. Lieberei,*[1] *J. Bauch,*[2] *and L. Gasparotto*[3]

[1] Institute of Applied Botany, Hamburg University
[2] Institute of Wood Biology, Hamburg University
[3] EMBRAPA Amazônia Ocidental, Manaus, AM, Brazil

Summary

The experimental study was carried out in order to evaluate in which way a sustainable growth of mixed plantation systems under the prevailing site conditions is possible. For this reason, the biomass production and the mineral element supply of six 2½-year-old plants of the high-quality wood species *Swietenia macrophylla* King including roots were determined. Up to twelve fractions (leaves, wood, bark, etc.) were separated and the element content (Ca, Mg, K, P, S, Fe, Al) of the different tissues was determined by Optical Emission Spectrometry (ICP-OES). The fractions allowed a high differentiation of the element content and can reveal physiological sinks within the plants. Parallel to this, the availability of nutrient elements in the soil was analyzed. As potassium is continuously transported from old to young leaves, this mineral element is „internally recycled". However, Ca accumulates in the old leaves and will, therefore, follow an „external recycling". The elements Al and Fe can be blocked in the cortex of the fine roots. The high demand for Ca, K, and P in the plant underlines that in the long run, a specific fertilization will be an urgent need, in order to guarantee a sustainable growth for high-quality timber trees. The low alkaline saturation of the soil and the low concentration of nutrient elements in the soil, which can only be improved immediately after burning for some months, reflect this insufficient nutrient supply.

Resumo

Produção de biomassa e o teor de elementos minerais de *Swietenia macrophylla* King na fase juvenil sob condições de plantio da Amazônia Central

Este estudo foi feito com o objetivo de avaliar de que maneira é possivel obter um crescimento sustentável de sistemas de plantio mistos sob determinadas condições locais. Para tal fim, foram determinados a produção de biomassa e o teor de elementos minerais de seis plantas de Mogno (*Swietenia macrophylla* King), espécie produtora de madeira nobre, com 2 anos e meio de idade. Paralelamente analisou-se a disponibilidade de nutrientes no solo. As plantas foram repartidas em até 12 frações (folhas, madeira, casca, raízes, etc.) e o teor dos elementos minerais Ca, Mg, K, P, S, Fe e Al foi determinado através de um Espectrômetro de Emissão Ótica (ICP-OES). As diversas frações mostraram uma grande diversidade com respeito ao teor de elementos minerais, o que implica a formação de determinados "depósitos fisiológicos" em locais determinados na planta.

Como Potássio (K) é transportado contínuamente das folhas velhas para as folhas novas, pode-se dizer que este elemento parece sujeito a uma "reciclagem interna". Por outro lado, Cálcio (Ca) tende a acumular-se nas folhas velhas, indicando uma "reciclagem externa". Os elementos Alumínio (Al) e Ferro (Fe) encontraram-se retidos localmente no córtex das raízes finas.

A alta demanda por Ca, K e P nas plantas mostra que, a largo prazo, uma fertilização específica torna-se imprescindível para garantir um crescimento sustentável de árvores produtoras de madeira nobre sob um regime de plantio. A baixa saturação alcalina e as reduzidas concentrações de elementos minerais no solo, que aumentam apenas por alguns meses após a queima, refletem esta insuficiência geral de elementos minerais no solo.

Introduction

Agroforestry systems with different native plant species seem to be a solution for a sustainable agriculture in the Amazon region – a region with extreme site conditions, where a high percentage of primary forest still is slashed and burned. Large areas are lost due to inexperienced non-site adapted agriculture. Furthermore, the knowledge about most of the native plants from the Amazon region, which potentially can be used for sustainable agroforestry systems, is still very low.

The aim of this study was to gain fundamental data on *Swietenia macrophylla* King, a highly valuable timber species, which may allow an evaluation, in which way a sustainable growth of this species in a suggested plant system is possible under the prevailing site conditions. In this respect, the biomass production and the mineral element supply of 2½-year-old plants of *Swietenia macrophylla* were determined. The plants were separated into different tissue fractions to allow a distinct differentiation in element content and to reveal physiological sinks within the plants.

The soils in the Amazon region are known to be very acid and poor in nutrients, a very important aspect for agroforestry systems containing tree species which already implicates a long-term use. For this reason, parallel to the biomass and element content studies of the plants, the effect of slash and burn, a common form of land clearing in this region, on the availability of nutrient elements in the soil was analysed.

Material and Methods

Swietenia macrophylla King, a mahogany species, which belongs to the *Meliaceae*, was chosen, because of its high economic value on the Brazilian wood market and particularly in export markets (Fig. 1). Depending on the prevailing site conditions, adult trees can reach a height between 24 and 50 metres and diameters from 0.5 to 2.5 metres (DAHMS, 1993). Because of its excellent manufacturing qualities and very good resistance against different weather conditions, the wood of *S. macrophylla* is considered to be among the best on the world market, and it can be used in a wide range.

The extraction of whole plants out of the experimental field (comp. DÜNISCH et al., 1999) would have caused extreme disturbances in the single systems. Therefore, it was inevitable to establish a reference area where plants, roots included, could be taken out for total biomass and element content determination. For a good comparison, this reference area bordered directly to the experimental field. Together with the experimental area, it was slashed and burned and, like four other species, *Swietenia macrophylla* was planted in rows and treated like the *Swietenia* plants in the experimental plots.

At an age of approximately 2½ years, six of these 28 plants grown from collected seeds from primary stands were sampled after measuring height and diameter of all of them. The total biomass of each plant including the roots was determined gravimetrically. Up to 12 fractions (young leaves, old leaves, wood, bark, roots etc.) were separated and prepared in association of a methodology from RADEMACHER (1986). The kiln-dry plant material was powdered in a mill (Retsch Zentrifugalmühle 82219) and with a microwave (MLS 1200), 500 mg of each sample was brought into solution with HNO_3. The element content (Ca, Mg, K, P, S, Fe, Al) in these solutions of the different plant tissues was determined by Optical Emission Spectrometry (ICP-OES). N was analyzed by Micro-Kjeldal. For the evaluation in which way a sustainable growth of this species in a suggested plant system under the prevailing site conditions is possible, some tissues of a 15-year-old *S. macrophylla* plant were analyzed equally.

Parallel to this, the availability of nutrient elements in the soil was analyzed before slash-and-burn, directly after burning and six months after. Therefore, soil samples in a depth down to 15 cm were taken, and the element content (Ca, Mg, K, P, S, Fe, and Al) in the water-soil solutions was determined by Optical Emission Spectrometry (ICP-OES).

Fig. 1: a) 2½-year-old plant with a height of ca. 2 metres and a diameter of approximately 4 – 8 cm.
b) Ca. 15-year-old *Swietenia* plant with good annual increment.
c) Fruit with fertile seeds for later natural regeneration.
d) Wood of an adult plant with high quality for veneer production.

Results

Biomass production

At an age of 2½ years, the six plants had reached a height between 1.31 and 2.75 metres and diameters between 2.9 and 6 cm (Table 1), which does not differ much from the averages of 2 metres respectively 4 cm of all 28 measured *Swietenia* plants.

The total biomass (dry weight) amounted to the average 1.75 kg with a range between 0.91 kg and 3.24 kg. This high variation between the six plants examined may be due to the fact that all of the trees were to a higher or lesser degree infected with *Hypsipyla grandella*, which causes great damage to the biomass production. Nevertheless, the results showed that with an average of nearly 64%, most of the biomass in these young plants was already fixed in the stem, while almost 21% was taken from the roots and only 15% was covered by the leaves.

Table 1: Tree height, diameter 20 cm above ground, and biomass dry weight of different plant fractions of 2½-year-old *Swietenia macrophylla* plants

Tree-number	Height [m]	Diameter in 20 cm height [cm]	Biomass dry weight						
			Roots [kg]	Roots [%]	Leaves [kg]	Leaves [%]	Stem [kg]	Stem [%]	Total plant [kg]
2	2.75	6.0	0.69	21.3	0.32	10.0	2.23	68.7	3.2
6	1.31	3.5	0.20	20.8	0.15	15.4	0.61	63.8	1.0
11	1.70	3.6	0.21	22.5	0.07	8.0	0.64	69.5	0.9
18	2.40	5.7	0.65	22.4	0.14	4.9	2.11	72.7	2.9
22	2.02	3.5	0.18	15.4	0.45	39.3	0.52	45.3	1.2
26	1.78	2.9	0.32	23.7	0.21	15.5	0.83	60.8	1.4
$\bar{x}$ n = 6	1.99 ± 0.52	4.20 ± 1.31	------	21.02 ± 2.93	------	15.52 ± 12.37	------	63.47 ± 9.86	1.77 ± 1.01

Element analyses

The results of the total element content determination demonstrated high values of all elements and a high range of each element between the six *Swietenia* plants. While iron only showed small variations of approximately 29% of the average, phosphorus displays variations of the average of around 57%, potassium around 62%, sulphur and aluminium around 67%, magnesium over 85% and calcium 87%. But as regards the single elements in each plant, it can be clearly demonstrated that the tendencies of element accumulation in the different plant tissues are the same in all six plants.

In all 2½-year-old *Swietenia* plants, calcium for example had the highest rate in each total biomass dry weight with values between 0.48% and 1.22%. For the six trees, 53% up to 90% of the total calcium content was found in the leaf tissues of each plant.

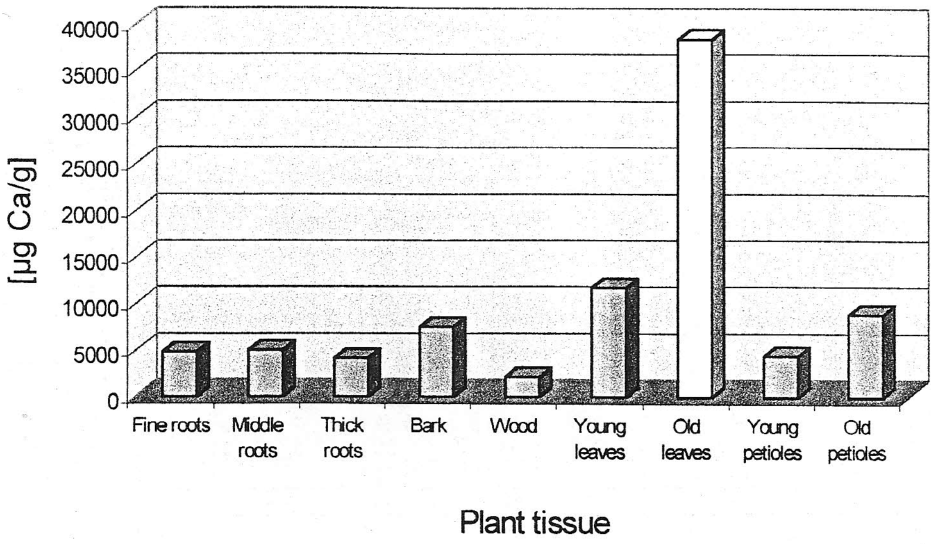

Fig. 2: Absolute calcium content in different plant tissues of an approx. 2½-year-old plant of *Swietenia macrophylla*

The relationship between biomass, element content per gram dry weight, and total element content, demonstrated in Table 2 with the data of one plant as an example, showed that physiological sinks within the plant essentially determine the growth of the plant. This can be demonstrated in particular by the Ca-content per gram dry weight of the old leaves (Fig. 2). The old leaves contain a biomass of only 12.5% of the total plant, but accumulate 56% of the total Ca-content of the plant (compare also Table 2).

Another example of the dependency of the plant growth from physiological sinks within the plant can be demonstrated by the results of potassium contents in the *Swietenia* plants. Potassium, after calcium, was found out to be the element with the highest values in the dry plant biomass with percentages between 0.3% and 0.57%. The total element contents of the different plant tissues (Table 2) demonstrate that with values between 5,000 ppm and 30,000 ppm, the highest potassium contents are found in the young leaf tissues (young leaves, young petioles). Compared with the absolute element contents of the other plant fractions, it can be shown that this species revealed a very intensive internal exchange for K from the old to the young leaves (Fig. 3).

Table 2: Quantitative determination of the biomass and element content of potassium, calcium, magnesium, phosphorus, sulphur, iron, and aluminium per g dry weight and average element content of a 2½-year-old *Swietenia macrophylla*

n. det. = not detectable

Plant fraction	Dry Weight		Potassium			Calcium		
			Content	Amount		Content	Amount	
	[g]	[%]	[µg/ kg]	[g]	[%]	[µg/ kg]	[g]	[%]
Fine roots	15.0	1.30	6,990.00	0.105	1.90	4,780.00	0.072	0.73
Middle sized roots	21.5	1.87	7,923.27	0.170	3.08	5,055.60	0.109	1.11
Thick roots	108.5	14.65	4,238.60	0.714	12.92	4,137.44	0.697	7.11
Σ Roots	205.0	17.82	—	0.989	17.90	—	0.878	8.95
Bark	114.3	9.93	5,256.34	0.601	10.87	7,462.58	0.853	8.70
Wood	520.7	45.26	3,352.32	1.746	31.57	2,084.72	1.086	11.07
Σ Stem	635.0	55.19		2.346	42.44	—	1.938	19.77
Young leaves	63.6	5.53	11,716.57	0.745	13.48	11,701.65	0.744	7.59
Old leaves	143.2	12.45	4,564.08	0.654	11.82	38,411.18	5.501	56.09
Young petioles	39.1	3.40	11,330.34	0.443	8.01	4,377.40	0.171	1.74
Old petioles	64.6	5.61	5,437.35	0.351	6.35	8,892.38	0.574	5.86
Σ Leaves	310.5	26.99	—	2.193	39.66	—	6.991	71.28
Σ Total plant	1,150.5	100	—	5.529	100	—	9.807	100
Average element content of the plant	————		0,48 %			0.85%		

Plant fraction	Magnesium			Phosphorus			Sulphur		
	Content	Amount		Content	Amount		Content	Amount	
	[µg/ kg]	[g]	[%]	[µg/ kg]	[g]	[%]	[µg/ kg]	[g]	[%]
Fine roots	935.00	0.014	1.09	498.00	0.007	0.85	881.00	0.01	1.43
Middle sized roots	914.47	0.020	1.53	453.52	0.010	1.11	698.86	0.015	1.62
Thick roots	374.29	0.063	4.91	221.54	0.037	4.24	347.99	0.059	6.34
Σ Roots	—	0.097	7.53	—	0.055	6.19	—	0.087	9.39
Bark	1,565.72	0.179	13.93	967.90	0.111	12.55	775.74	0.089	9.58
Wood	409.61	0.213	16.60	742.75	0.387	43.89	339.42	0.177	19.10
Σ Stem	—	0.392	30.53	—	0.497	56.45	—	0.265	28.68
Young leaves	1,840.69	0.117	9.11	1,327.89	0.084	9.58	2,124.94	0.135	14.60
Old leaves	2,919.14	0.418	32.54	1,028.52	0.147	16.72	2,631.78	0.377	40.72
Young petioles	1,229.54	0.048	3.74	1,688.21	0.066	7.49	494.72	0.019	2.09
Old petioles	3,292.40	0.213	16.55	487.70	0.032	3.58	647.94	0.042	4.52
Σ Leaves	—	0.796	61.94	—	0.329	37.36	—	0.57324	61.94
Σ Total plant	—	1.285	100	—	0.9	100	—	0.9	100
Average element content of the plant	0.11%			0.08%			0.08%		

Plant fraction	Iron			Aluminium		
	Content	Amount		Content	Amount	
	[µg/ kg]	[g]	[%]	[µg/ kg]	[g]	[%]
Fine roots	522.00	0.008	16.52	3,880.00	0.058	31.77
Middle sized roots	385.54	0.008	17.48	2,549.04	0.055	29.92
Thick roots	50.28	0.008	17.87	294.38	0.050	27.08
Σ Roots	—	0.025	51.87	—	0.163	88.76
Bark	38.33	0.004	9.24	n. det.	n. det.	n. det.
Wood	6.09	0.003	6.69	n. det.	n. det.	n. det.
Σ Stem	—	0.008	15.93	—	0.000	0.00
Young leaves	56.00	0.004	7.51	47.25	0.003	1.64
Old leaves	63.61	0.009	19.21	76.51	0.011	5.98
Young petioles	26.67	0.001	2.20	63.63	0.002	1.36
Old petioles	24.05	0.002	3.28	63.99	0.004	2.26
Σ Leaves	—	0.015	32.20	—	0.02058	11.24
Σ Total plant	—	0.05	100	—	0.2	100
Average element content of the plant	0.004%			0.02%		

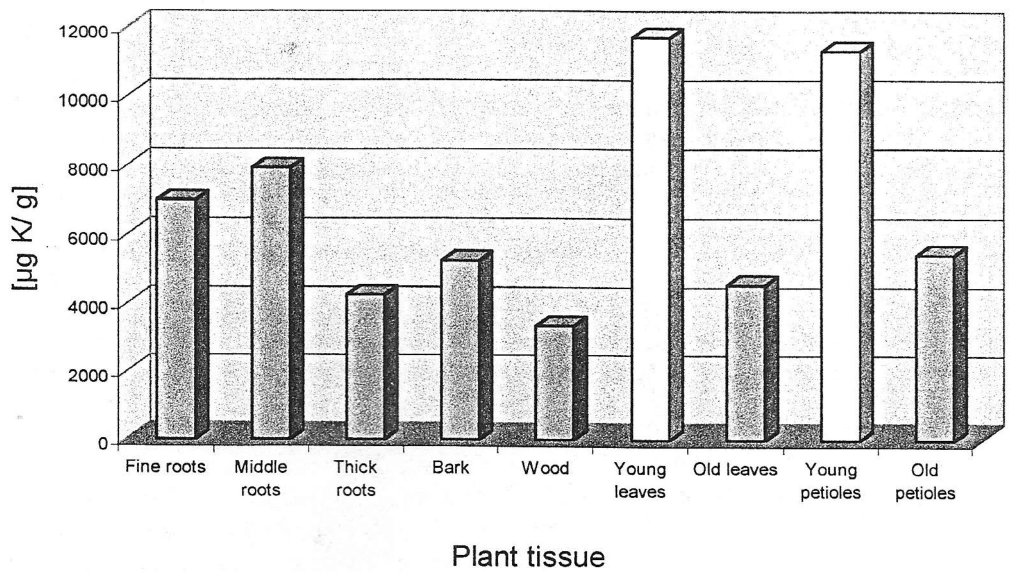

Fig. 3: Absolute potassium content in different plant tissues of a 2½-year-old plant of *Swietenia macrophylla*

Table 2 reveals for Ca, as well as for Mg, the highest element contents in old leaves. In total, 61.94% of Mg is located in the leaves. Also for P and S, the trend to maximum concentrations in old leaves is obvious.

Referring to the absolute aluminium and iron contents in the different plant fractions, it can be demonstrated that *Swietenia macrophylla* shows protection barriers in the roots against these toxic elements. (Table 2) While the fine roots accumulated up to 3,880 ppm aluminium, this value was reduced to contents between 240 ppm – 488 ppm in the thick roots and to values under 100 ppm in the leaves. Similar results were found for iron with absolute contents ten times lower than the ones of aluminium.

The element data of the individual tree demonstrated in Table 2 show 0.48% K, 0.85% Ca, 0.11% Mg, 0.08% P, 0.08% S, 0.004% Fe, and 0.02% Al related to the dry weight of the plants. These figures particularly indicate a high mineral element demand.

The absolute element contents of the tissues analyzed from a 15-year-old *Swietenia* tree showed some changes compared to the 2½-year-old plants. They demonstrate a significant increase of potassium, calcium, and magnesium in the roots during plant growth. The extremely high values of calcium which were found in the old leaves of the 2½-year-old plants could not be observed in the tissues of the older plants. But even in this case, also the 15-year-old plant showed significant differences between the calcium content of old and young leaves.

Soil analyses

The analyses of the soil samples demonstrated a very low alkaline saturation of these soils of maximally 5 – 13% before slash-and-burn. After slash-and-burn, the values raised up to 26 and 53%, but six months later, they were already reduced again to figures between 5 and 26%.

As demonstrated in Fig. 4, slash-and-burn of the area caused a significant change in the different element contents of the soil samples. The distinctly higher values of calcium, potassium, magnesium, and sulphur, and to a lesser degree manganese and sodium, directly after burning lead to the conclusion that these elements were released by burning the plant material. Especially the soil contents of potassium and calcium demonstrate this effect very distinctly. While the absolute values for potassium before slash-and-burn lay between 2.06 and 4.61 ppm, and the ones for calcium around an average of 1.53 ppm, they increased after burning to a range from 5.81 to 31.05 ppm and an average of 14.68 ppm respectively. But like magnesium and sulphur that raised about 50%, manganese about 10% and sodium about 15% after burning, six months after this event also potassium and calcium reached almost the values of the soil samples before slash-and-burn (Fig. 4).

Aluminium and iron demonstrated the contrary effect. While iron showed a slight decrease after burning, the aluminium content was significantly reduced by slash-and-burn, and even six months after this did not reach the initial level, which was determined in the soil samples before burning.

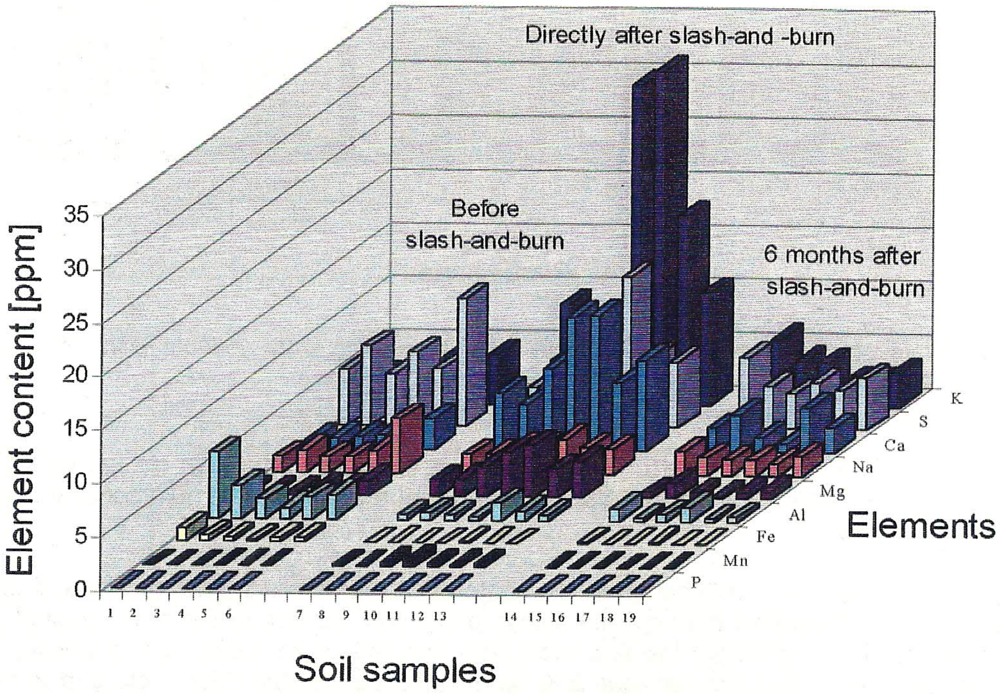

Fig. 4: Element content of 19 different soil samples before slash-and-burn, directly after burning, and six months after slash-and-burn. Numbers on the abscissa indicate samples. Soil solution evaluated in a depth of 0 to 30 cm.

Discussion

The biomass determination demonstrated that tropical wood species can reach a higher biomass production in the same time than species from areas with a moderate climate. The results of the element analyses in the different *Swietenia* plants showed that those plants have a high need of nutrient supply, especially for calcium, potassium and phosphorus.

While KLINGE (1976) demonstrated a low calcium value in the leaf compartment during his investigations in a rainforest near Manaus, the results of this investigation in contrast showed extremely high concentrations of calcium in the leaves. It is known that calcium, because of its low mobility, cannot be mobilized any more after deposit, and that it usually is accumulated in the old leaf compartments (AMBERGER, 1983; MARSCHNER, 1986). But the measured values between 53 and 90% of the whole calcium content referring to the dry weight of one 2½-year-old *Swietenia* plant are extremely high. The accumulation of calcium in the old leaves with an average of approximately 49% shows a very effective recycling system in which Ca can be reused after litter fall. This allows the plant a reduction of her dependency of the extremely low rates of Ca available to the plants in the soil of the Amazon region that is poor of limes (KLINGE, 1976; SALATI and VOSE, 1984).

The plant toxic element aluminium can lead to a high inhibition of the root development as shown by investigations of GOBOLD et al. (1988) with spruce seedlings (*Picea abies*). In contrast to this plant species, which is not adapted to acid soils, *Swietenia macrophylla* demonstrates a good adaptation to the acid oxisoils of the investigated location which are rich in aluminium (FITTKAU, 1983). This adaptation of native plant species, which shows protection barriers against aluminium, was already observed but not closely investigated by FURLANI (1989).

The results of the soil analyses proved that the soils of this "terra firme" area exhibit an extreme lack of nutrients, as also described by KLINGE (1976) and JORDAN (1982). Slash-and-burn is a generally used form of land clearing in the Amazon region and, as demonstrated, this method sets free mineral elements. Investigations on a location with pasture point out that the amount of nutrients liberated depends on the vegetation form used before slash-and-burn. The pasture, poor of high stocks of biomass-producing plant species, did not display equal effects as observed in this work. Only small increases of calcium and potassium could be found (McKERROW, 1992). In accordance to the data presented here, BRINKMAN and NASCIMENTO (1973) made similar observations on the decrease of iron and aluminium contents after burning. As also described in this work, BRINKMAN and NASCIMENTO (1973) demonstrated that there is only a short-term fertilizer effect caused by slash-and-burn due to leaching of the released nutrients.

In order to get information about the possibility whether these acid soils poor of nutrients are useful for long-term plantations, the relation of the mineral element content in the soil and the mineral element need of the plants had to be established. Therefore, the mineral element need of 10-year-old plants was calculated, assuming a linearly growing biomass production as wood species usually do (BRÜNIG, 1971). For a 10-year-old non-fertilized plant with a dry weight of about 58 kg and a percentage of the leaf compartments of about 10, stem about 60 and roots about 30%, the following element demand can be calculated: 27.5 g K, 49 g Ca, 6.6 g Mg, 4.5 g P, and 4.5 g S. With a plant distance of 6 x 7 metres, 240 *Swietenia* plants can be used per hectare monoculture. On such an area, 6.6 kg K, 11.76 kg Ca, 1.58 kg Mg, 1.08 kg P, and 1.08 kg S would be fixed in the plant material. Comparing this data with the element stock of the soils in the Amazon region, it can be demonstrated that long-term agroforestry with wood species without fertilization will not be possible.

Conclusions

The results of the biomass determination demonstrated that tropical plants like *Swietenia macrophylla* are able to reach a high biomass production in a very short time. In agreement to this, the element analyses showed a high mineral element demand of the plant species. Besides, *Swietenia macrophylla* have internal and external recycling systems at their disposal. The species revealed a very intensive internal exchange for K from the old to the young leaves (internal recycling), whereas Ca extremely accumulates in the old leaves to be reused after litter fall (external recycling). In addition to this, the plants showed protection barriers against aluminium.

The soil analyses indicated poor nutrient supply conditions. The fertilizer effect caused by slash-and-burn was only short-termed.

The relation of the mineral element content in the soil and the mineral element need of the plant points out that specific fertilization for each plant species is necessary. Gradually disintegrating fertilizer (mulching) and mixed cultures from annual and perennial species with priority to the native species are the only possibility of sustainable agriculture in the Amazon region.

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