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SHIFT Project ENV 45
BMBF No. 0339641 5

Water and nutrient fluxes as indicators for the stability of different land use systems on the Terra firme near Manaus

Annual Report 1997

Annex: Scientific results

1) Distribution of throughfall and stemflow in agroforestry, perennial monoculture, fallow and primary forest in the central Amazon, Brazil

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Introduction

Rain falling on vegetated ground may either be intercepted by the canopy and be evaporated directly, or it may reach the soil as throughfall or stemflow after a more or less intensive contact with the plants' surfaces, especially leaves and bark. During this contact, mineral and organic substances are exchanged between the water and the plant or, if present, an epiphytic cover (Jordan, 1978; Coxson et al., 1992). As a result, the vegetation influences the quantity, quality and distribution of rain water passing through the canopy before it reaches the soil.

Interception loss reduces the amount of plant available soil water, whereas the partitioning of the remaining water into throughfall and stemflow decides about the spatial distribution of the water input at soil level. In forest ecosystems, stemflow contributes normally only a few percent to the total water input into the soil, but in contrast to open-area rainfall and throughfall, it is a point source of water which may cause high water supply rates and consequently high infiltration in a small area around individual tree stems (Pressland, 1976; Tanaka et al., 1991; Tanaka et al., 1996; Taniguchi et al., 1996). On the one hand, this may give the respective trees preferential access to the nutrients dissolved in the stemflow. On the other hand, on highly permeable soils such as many tropical Ferralsols, the undesirable result of the stemflow may be rapid leaching of nutrients out of the rooting zone of the plants in the immediate vicinity of the trunk.

The partitioning of rainwater into interception loss, throughfall and stemflow depends on properties of the plant stand, which are determined by the spatial arrangement of the plants, and by characteristics of the plant species present, such as their leaf area and branch angles (Jordan, 1978). Consequently, heterogeneous vegetation such as tropical forest or polyculture systems including homegarden-like systems and other types of agroforestry may consist of a mosaic of different situations with respect to the quantity and quality of water inputs into the soil. Understanding the consequences of the presence of a certain tree species in a land use system on the hydrological processes in this system including water distribution, infiltration and nutrient leaching may be a step in the optimisation of land use systems. This may be most important under conditions of high rainfall and low nutrient availability, a combination frequently encountered in the humid tropics.

The stand hydrology of both tropical forests (Jordan, 1978; Jordan and Heuveldop, 1981) and antropogenic ecosystems involving a tree component (Imbach et al., 1989; Opakunle, 1991) has been studied, and the spatial variability of hydrological parameters under a tree canopy has been emphasised (Lloyd and Marques, 1988; Lin et al., 1997). However, little information is available concerning the relationships between these spatial aspects of water distribution and the influence of particular tree species in heterogeneous land use systems including the consequences for management. To obtain such information, we monitored throughfall and stemflow in relation to the presence of four cultivated and three spontaneous tree species, one of them under two management regimes, in a perennial polyculture (agroforestry), three monoculture plantations, spontaneous fallow and primary rainforest in the Amazon basin near Manaus, Brazil. The study was conducted during one year as part of a larger experiment on the recuperation of abandoned land with perennial polycultures.

Materials and methods

The following plantation systems were included in the study: A polyculture with peachpalm (*Bactris gasipaes*) both for fruit and for palmito (heart of palm) production, cupuacu (*Theobroma grandiflorum*, a close relative of cacao), Brazil nut (*Bertholletia excelsa*) and urucum (*Bixa orellana*) with a cover crop of tropical kudzu (*Pueraria phaseoloides*) in the interspaces between the trees (Fig. 1); a monoculture of peachpalm for palmito, planted at 2 by 2 m; a monoculture of peachpalm for fruit, planted at 4 by 4 m with an understorey of peachpalm for palmito at 2 by 2 m spacing; and a monoculture of cupuacu, planted at 7 by 6.4 m, equally with a *Pueraria* cover crop. All these species are of major commercial interest in Amazonia. Peachpalm was used in the Latin American lowland humid tropics since pre-Columbian times, and significant research efforts have been invested in the improvement of the species (Clement and Mora Urpí, 1987; Clement, 1988). Urucum is planted for its non-toxic red dye in numerous tropical countries of Latin America, Asia and Africa. Brazil nut trees are planted both for their nuts and their excellent wood, although most of the Brazil nuts on the market still come from wild trees. Cupuacu is planted for its fruit pulp which serves for the preparation of juices and sweets (Rehm and Espig, 1984).

In May 1996, the average height and stem diameter of the trees was as follows. Peachpalm for fruit in polyculture: 8.9 m and 17.1 cm (at 130 cm, n=37); peachpalm for fruit in monoculture: 10.3 m and 16.5 cm (at 130 cm, n=23); Brazil nut: 5.3 m and 8.2 cm (at 130 cm, n=48); cupuacu in polyculture: 2.6 m and 5.5 cm (at 20 cm, n=60); cupuacu in monoculture: 1.9 m and 4.2 cm (at 20 cm, n=36); urucum: approximately 3 m and 10 cm (at 20 cm); peachpalm for palmito: approximately 3 to 4 m height. The approximate ground areas which were influenced by the crowns of the trees are given in Tab. 4. These were determined from the horizontal extension of the longest branch of the respective trees, which gives a high estimate for the crown area. Allometric relationships and biomass estimates for the species will be published in a separate paper.

Plots with spontaneous vegetation of the same age as the agricultural plots were included in the study. These were dominated by *Vismia* spp., which is a characteristic genus in the vegetation of young fallows and degraded lands in the region. On the average, there were 1.95 (S.E.=0.17) *Vismia* stems per m^2 in the fallow plots. In addition, we included two tree species from a nearby primary rainforest: *Eschweilera* sp. („Matá-matá"), a dicotyledoneous tree, and *Oenocarpus bacaba* („Bacabeira"), a palm. Both species are relatively frequent in this forest and are of commercial interest, *Eschweilera* for its wood and *Oenocarpus* for its fruits which are collected by the local population for the preparation of juice.

The measurement plots with the exception of the rainforest sites, but including the fallow plots, were arranged in a randomised complete plot design with five replications, three of which were used in this study. For the primary forest species, three individuals of each species were chosen in a forest adjacent to the experimental area. Plot size was 24 by 32 m in the peachpalm monocultures and 48 by 32 m in all other treatments. The polyculture was studied at two fertilisation levels, full fertilisation according to local experiences (research-based recommendations do not exist for these species in the region) and 30% of this fertilisation level (low input). The monoculture plots were only studied at the higher fertilisation level (100%). All plots had been planted in February/March 1993 with bag plants and had been 3 to 4 years in the field when the measurements were conducted. The peachpalm for palmito was managed by cutting the main stem 1½ years after planting and harvesting the offshoots three times per year when they reached a diameter of 8 cm at 1 m height. Urucum was cut back at about 1.5 m height once per year after the harvest between March and May to increase fruit production, removing all the leaves and the small branches. The other species did not receive any management of relevance for this study.

Open-area rainfall was measured with two polyethylene-collectors in open locations in each of the three blocks. The collectors were placed at about 70 cm above the soil and had a diameter of 7.4 cm (9.3 cm during the last month of the study). A narrow bottleneck prevented evaporation of collected water. Throughfall was measured with similar collectors under six well-developed, but not exceptional trees per species and cropping system. In each of the 6 polyculture plots (2 fertilisation levels, three replications), one tree per species was chosen, and in the monoculture and fallow plots, two trees per species were chosen. The collectors were placed at two opposite sides of the stem in EW-direction, both at 40 cm and at 150 cm stem distance. This was to detect eventual effects of exposition caused by the predominantly eastern winds (O.M.R. Cabral, 1994, unpublished). In the cupuacu monoculture plots, the 150 cm distance was only sampled at two instead of six trees because the crowns of most trees did not reach this distance. In the peachpalm monocultures, only one set of collectors was used for each tree because wind was assumed to be unimportant in these rather dense plant stands, and the 150 cm collectors were placed on the diagonal between neighboring plants. In the fallow, two collectors per plot were positioned at random in the plots. In the primary forest, throughfall was measured at 40 cm from the stem with two collectors at opposite sides of each measurement tree. No measurements were conducted on the ground vegetation and the litter, so that all throughfall data in this study refer to the tree layer only.

Stemflow was measured at the same trees as throughfall. Polyurethane collars as described by Likens and Eaton (1970) were placed around the stems, and the stemflow was collected in plastic containers. As some species (especially peachpalm for fruit, see below) produced a very high stemflow, we collected stemflow and throughfall every day following a rain event to reduce data losses due to overflow of the containers (on Mondays, the throughfall and stemflow of the three foregoing days, if any, was collected). Although we increased the capacity of the stemflow containers of the most „productive“ individuals to a final volume of 160 l, this was not sufficient for the heaviest rain events. As a result, the stemflow data of peachpalm and Brazil nut are somewhat biased because the highest values were lost due to overflow, especially at the beginning of the study. The stemflow collars had to be checked frequently for leakage because of the rapid growth of some species, especially the peachpalm offshoots.

Calculations and statistical analysis

The throughfall measured in a single collector was summed for the whole measurement period and was divided by the rainfall measured in the open-area rain collectors from the same block to give the total throughfall measured in this position in percent of the open-area rainfall. The results from the two corresponding measurement positions on opposite sides of the same tree in the polyculture plots showed no consistent differences, and they were therefore averaged and treated as a single value in the data analysis. Stemflow measured at the same tree was also summed over the measurement period and divided by open-area rainfall to give liters of stemflow per mm of open-area rainfall for each tree. The result of these transformations was one value per measurement tree for each of the three variables, throughfall at 40 and 150 cm stem distance and stemflow (Tab. 3). In addition, we created an approximate index for characterising the total water input near the stem by assuming that all stemflow infiltrated within an area of 2 m^2 around the stem (radius 80 cm) and that the 40 cm throughfall collector measured the throughfall in the same area. This infiltration area of the stemflow is somewhat higher than the maximum infiltration areas determined in other studies (radius 50 to 70 cm; Pressland, 1976, Tanaka et al., 1991), but these studies did not include palms with their very high stemflow rates (see below). We divided the stemflow by the open-area rainfall corresponding to this area and added the throughfall from the 40 cm collector in percent of the open-area rainfall to this value to obtain the total amount of water reaching the soil in the proximity of the stem in percent of the open-area rainfall (Tab. 3).

Species comparisons were calculated by ANOVA. In case of a significant F-test at $p<0.05$, this was followed by mean separations with Duncan's multiple range test, also at $p<0.05$. First, we compared the fertilisation levels of the polyculture plots and found no significant effect for any of the investigated variables (data not shown). In the following, fertilisation levels were ignored and all polyculture plots were considered replicates. In the monoculture and the fallow plots, we treated all the measurement trees (two trees per plot) as independent replicates, because we had chosen trees of different size in each plot wherever possible, and there was no reason to believe that for a certain species, within-plot variability of crown hydrology was smaller than between-plot variability. So, there were six replicate individuals per species and per cropping system, with the exception of the primary forest with only three replicates per species.

The effect of tree size on stemflow for the different species was tested by correlating the amount of stemflow per mm of rainfall with the cironference) of the stem of the respective tree as measured on the 17th October 1996, i.e. approximately in the middle of the measurement period. For peachpalm for palmito, the circonferences were taken from the beginning of the experiment in March 1996. For peachpalm for fruit and Brazil nut, circonference measurements were taken at the conventional breast height of 130 cm, for the other trees at 20 cm because their stems split up little above that height, and for the peachpalm offshoots at 60 cm where circonference measurements were easiest to carry out.

Results

Between 19 March 1996 and 26 March 1997, a total of 2352 mm of open-area rainfall was measured in 107 collections (Tab. 1). This is about 10% less than the rainfall of an average year. Only few rain events were not included in the measurements, e.g. cases when several rains during a weekend caused overflow of a large proportion of the collectors, or during the Christmas holydays.

Tab. 1: Amount of open-area rainfall collected during the measurement period (19 March 1996 to 26 March 1997)

Month	Rainfall collected		Month	Rainfall collected	
	Events	mm		events	mm
Mar 96	3	15.8	Oct 96	9	167.6
Apr 96	15	362.5	Nov 96	6	172.4
May 96	10	137.2	Dec 96	8	246.0
Jun 96	7	216.8	Jan 97	12	165.5
Jul 96	6	110.3	Feb 97	7	192.2
Aug 96	10	265.9	Mar 97	7	239.8
Sep 96	7	60.5	Total	117	2352

Tab. 2: Results of the Analysis of Variance for all tests

Independent variable	df Effect	df Error	F	p	Species included
Throughfall 40 cm	12	59	10.73	<0.001	all
Throughfall 150 cm	9	46	6.71	<0.001	all except fallow and forest
Stemflow	10	49	16.80	<0.001	all except Pueraria
Throughfall + stemflow near stem	12	59	4.49	<0.001	all

Throughfall

The ANOVA detected a significant species effect on throughfall at both 40 cm and 150 cm tree distance (Tab. 2). The mean values per species are given in Tab. 3. Fig. 2 shows throughfall values on a schematic transect through a polyculture plot. Within the polyculture plots, throughfall values at 40 cm stem distance ranged from less than 50% of the open-area rainfall under peachpalm for palmito to over 100% under the urucum and Brazil nut crowns. In the open areas between the trees in the polyculture plots, at 4 m from neighboring palms and 3.5 m from neighboring dicot trees („*Pueraria*“ positions in Tab. 3), the throughfall was slightly reduced in comparison to the open area rainfall, presumably because of interception of rain by the surrounding trees when the rain events were accompanied by wind. In the part of the plots where peachpalm was managed for fruit, the interception tended to be higher than in the part where the palms were regularly pruned for the harvesting of palmito and were consequently much smaller in size. However, this difference was not significant (Tab. 3).

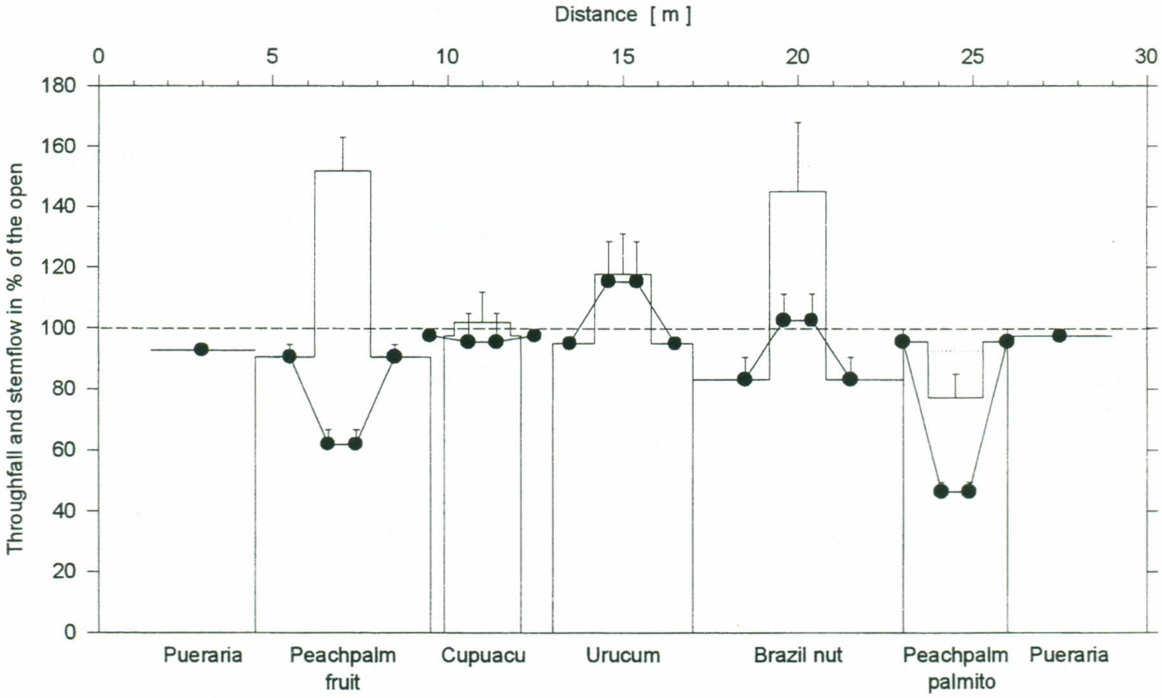

Figure 2: Transect through a polyculture plot, giving the throughfall at 40 and 150 cm stem distance (point graphs) and the sum of throughfall and stemflow (bar graphs, means and S.E.). It was assumed that the collector at 40 cm stem distance gave representative throughfall values for a circular area with a radius of 80 cm around the stem in which also all stemflow infiltrated, and that the collector at 150 cm stem distance gave representative throughfall values for the remaining part of the area covered by the crown of the respective tree (Tab. 4). For peachpalm for palmito,

the firm line indicates the normal case with two offshoots per plant, and the dotted line indicates the case with three offshoots per plant. The width of the bars at their base corresponds to the mean crown diameter of the respective tree species.

The palms intercepted more rain than the dicot trees and differed also from these in the spatial pattern of interception. Close to the stem (40 cm), the interception was much higher than in the peripheral parts of the palm crowns (150 cm). This was a consequence of the typical curvature of the palm leaves, first upward and then downward, and the pronounced groove on the upper side of the petioles. Because of this leaf form, much of the rain falling on the central part of the leaves (40 cm stem distance) was channelled either to the stem where it produced very significant amounts of stemflow (see below), or was directed away from the stem and dropped from the hanging outer parts of the leaves. At 150 cm from the stem, the palm leaves were already inclined downward, and apparently a greater part of the rain falling on the leaves dropped down from the leaflets. The canopy was also less dense here than closer to the stem.

Tab. 3: Throughfall at two stem distances, stemflow and total water input near the stem in different land use systems in central Amazonia as a function of the tree species present. Inputs „near stem“ refer to an area of 2 m^2 around the stem of the respective tree, with the exception of the fallow where they refer to the whole plot area (see methods section). Values within columns followed by the same letter are not different at $p < 0.05$ (Duncan's Multiple Range test).

Species	Throughfall		Stemflow	Waterinput near stem	
	40 cm	150 cm		stemflow	total
	% of the open		liter mm^{-1}	% of the open	
<u>Polyculture</u>					
Peachpalm fruit	61.9 de	90.5 abc	1.80 a	89.9	151.8 a
Peachpalm palmito	46.4 e	95.6 abc	0.62 b	30.8	77.2 c
Cupuacu	95.4 abc	97.4 ab	0.13 c	6.6	101.9 bc
Brazil nut	102.5 ab	83.1 bc	0.85 b	42.6	145.0 a
Urucum	115.3 a	95.0 abc	0.05 c	2.6	117.9 ab
Pueraria (fruit side)	92.7 abc	92.7 abc			92.7 bc
Pueraria (palmito side)	97.4 abc	97.4 ab			97.4 bc
<u>Monocultures</u>					
Peachpalm fruit	50.3 e	63.0 d	1.48 a	73.8	124.1 ab
Peachpalm palmito	52.3 e	81.8 c	0.82 b	41.2	93.5 bc
Cupuacu	82.1 bcd	98.5 a	0.12 c	6.0	88.1 bc
Fallow	76.6 cd		0.10 c	20.3	96.9 bc
Forest (*Eschweilera*)	76.2 cd		0.05 c	2.6	78.8 c
Forest (*Oenocarpus*)	95.9 abc		0.46 bc	23.2	119.1 ab

In contrast to the palms, the dicot trees Brazil nut and urucum had higher throughfall close to the stem than under the peripheral crown parts. For Brazil nut, this was a consequence of the relatively sparse foliage in the interior part of the crown, where no interception losses were measured, whereas the foliage of the more peripheral crown parts reduced the throughfall by 17%. Urucum, on the other hand, had very little interception in the peripheral crown parts, but tended to increase the throughfall at 40 cm stem distance to values over 100% (Tab. 3). This increase was presumably a result of the channelling away from the stem of rain falling on the central part of the crown by the outward-inclined, soft leaves. This resulted in particularly low stemflow rates for this tree species (see below). Cupuacu had little influence on rainfall distribution. The peripheral measurement positions were in most cases outside or at the outer limit of the area covered by the canopy of these trees (Fig. 2).

The measurements from the peachpalm monocultures (for fruit and for palmito) confirmed in principle the results from the polyculture systems (Tab. 3). The throughfall in the peripheral measurement position (150 cm from the stem) was however lower than in the polyculture, because in the dense monoculture stands the crowns of neighboring palms overlapped and formed a more or less continuous canopy. The lowest throughfall was measured in the peachpalm monoculture for fruit, with however a large amount of stemflow (see below). This low throughfall was partly a result of the understorey of peachpalms for palmito. The association of peachpalm for fruit and palmito was tested in this experiment, but proved to be agronomically unfavourable and would not normally be recommended because of the intense intraspecific competition. The rain interception of a pure fruit palm plantation would have been less than in this experiment. In the cupuacu monoculture, there was some rain interception close to the stems, but the outer measurement positions were normally beyond the limits of the crowns of these trees, which developed much slower than in the polyculture plots (see crown areas in Tab. 4).

With 77% of the open-area rainfall, the throughfall in the fallow plots was lower than in the agricultural plots with the exception of the areas close to the palms. In the primary forest, the throughfall at 40 cm from the palm *Oenocarpus* tended to be higher than under the dicotyledoneous *Eschweilera*, apparently because of the much larger crown of the latter. However, with only three replications per species, the difference was not significant (Tab. 3). There was also some interference of the crowns of neighboring trees, which tended to obscure species-specific effects on throughfall distribution.

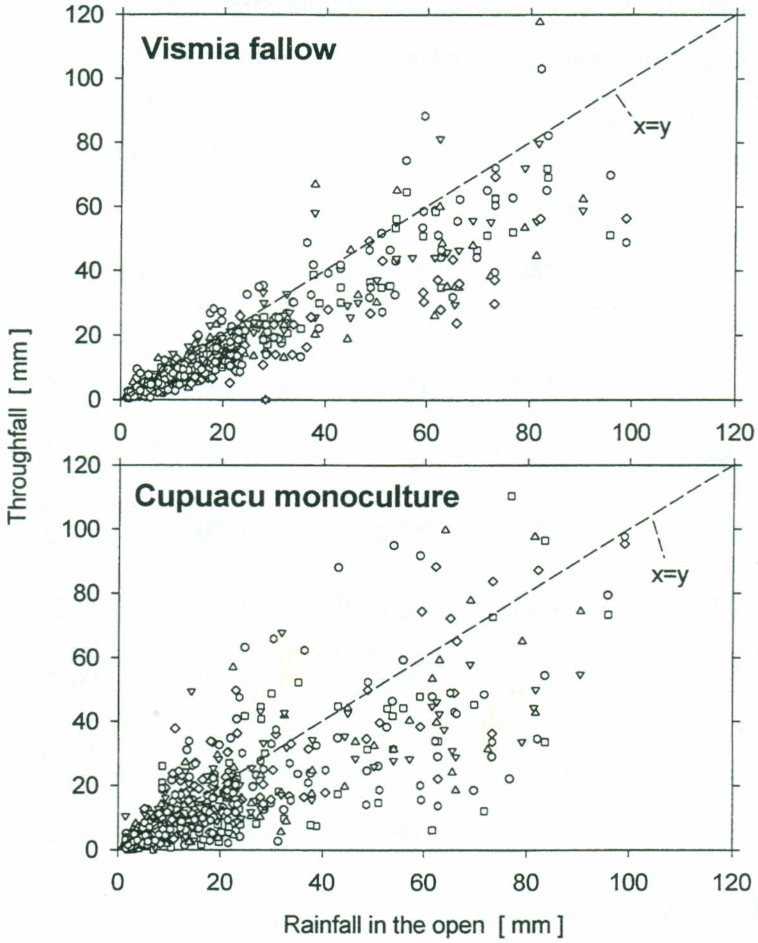

Figure 3: Variability of the throughfall in the *Vismia* fallow and in the cupuacu monoculture, at 40 cm stem distance, for single rain events in relation to the open-area rainfall. The different symbols correspond to the six measurement trees per species.

Summed up over the whole measurement period, the throughfall values of the replicate trees per species were sufficiently close to each other to yield significant species differences, although the variability of the throughfall for individual rain events could be very high. The relationship between throughfall and open-area rainfall for the relatively homogeneous *Vismia*-fallow is in sharp contrast to the extreme variability of the cupuacu data (Fig. 3). Under the cupuacu canopy, some spots received almost no precipitation even at rain events of 20 to 30 mm, whereas other spots received more than twice the open-area rainfall. This was certainly due to the large leaves of cupuacu which effectively channelled the intercepted rain away from some spots and concentrated it under their drip-tips. The small-scale redistribution of the rain by the smaller leaves in the *Vismia* canopy was apparently much less. A high variability between individual rain events was also observed in most other sampling positions.

Tab. 4: Throughfall, stemflow and total water input and contribution of the different tree species present in different land use systems in central Amazonia. The values for the primary forest species refer to an area of 2 m^2 around the stem.

Species	plants ha^{-1}	crown area		stemflow	throughfall	total
		m^2 per tree	% of plot area	% of open-area rainfall		
Polyculture						
Peachpalm fruit	78.1	19.5	15.2	1.4	13.3	14.7
Peachpalm palmito	156.3	~4	6.3	0.96	4.4	5.4
Brazil nut	93.3	29.4	27.4	0.79	23.2	24.0
Cupuacu	93.3	3.51	3.3	0.12	3.2	3.3
Urucum	156.3	~12.5	19.5	0.08	19.2	19.3
Pueraria			28.3		26.9	26.9
Total			100	3.37	90.2	93.5
Peachpalm for fruit monoculture						
Peachpalm fruit	625	~16	100	9.22	61.4	70.6
Peachpalm palmito	1875	~4	75	15.5		15.5
Total			175	24.7	61.4	86.1
Peachpalm for palmito monoculture						
Peachpalm palmito	2500	~4	100	20.6	67.1	87.7
Cupuacu monoculture						
Cupuacu	223.2	1.3	2.8	0.27	2.0	2.3
Pueraria			97.2		97.2	97.2
Total			100	0.27	99.2	99.5
Fallow						
Vismia	19500	0.513	100	20.3	76.6	96.9
Primary forest						
Eschweilera				2.6	76.2	78.8
Oenocarpus				23.2	95.9	119.1

Tab. 4 gives the total throughfall per system and the contribution of each species to it. The highest throughfall was measured in the cupuacu monoculture due to the small number of trees per hectare and their limited crown area. The peachpalm monocultures for fruit and for palmito had the lowest throughfall. Polyculture, fallow and primary forest lay between these extremes.

Stemflow

Tab. 3 gives the stemflow per measurement unit in liter per mm of open-area rainfall. The measurement unit was the tree in all cases except peachpalm for palmito, where the unit was the individual offshoot, and in the *Vismia* fallows, where the unit was the stem. Several such stems belonged to the same plant, although it would have been difficult to decide which ones without excavation of the belowground organs.

With more than 1 liter per mm of rain, peachpalm for fruit had significantly higher stemflow than all other species. It was followed by the other palms, peachpalm for palmito and the forest palm *O. bacaba,* as well as Brazil nut with values between 0.4 and 1 l mm^{-1}. The other species produced less than 0.2 l mm^{-1} of stemflow. There were no significant differences for the same species between monoculture and polyculture plots.

For Brazil nut, stemflow differed by a factor of 17 between the six measured individuals and, on the average, strongly increased with tree size (Fig. 4). Similarly, a positive correlation between circonference and stemflow was found for the peachpalm offshoots and, much less pronounced, for the *Vismia* fallow. Increases of stemflow or, correspondingly, of the area of stemflow infiltration with tree diameter have also been reported by Rutter (1963), Pressland (1976) and Tanaka et al. (1991). For peachpalm for fruit, in contrast, stemflow was negatively related to tree size, i.e. thinner trees had higher stemflow than thicker trees (Fig. 4). This result was independent of the cropping system (mono- or polyculture). The reason for this relationship is not clear. There was no evidence that thinner palms differed in height or canopy structure (e.g. leaf angles) from thicker palms. For the smaller dicot trees, cupuacu and urucum, stemflow was not significantly correlated with stem circonference, in agreement with Opakunle's (1991) data for cacao.

Water input proximate to the stem

The bar plots in Fig. 2 give the sum of throughfall and stemflow for every species in percent of the open-area rainfall, calculated for a 2 m^2 area around the stem (see Methods section). This value has to be considered an index and not a quantitative measure of water input, because the area in which the stemflow infiltrated for different species, tree sizes and rainfall intensities has not been determined in this study. In other studies, maximum radii of 50 cm (Pressland, 1976) and 70 cm (Tanaka et al., 1991) were determined within which even for large trees, all stemflow infiltrated into the soil, but these studies did not include palms with their very high stemflow rates. So, for the species with little stemflow in our study (urucum and cupuacu), the area of stemflow infiltration may have actually been smaller than assumed, and the total water input in this reduced infiltration zone in percent of the open-area rainfall would then have been higher. However, in view of the numerous sources of variation of the infiltration area both within plots and between rain events, our index seems to be adequate for the purpose of species comparisons.

In the polyculture plots, peachpalm for fruit and Brazil nut were the species which concentrated significantly more water near their stem than the open-area rainfall (Fig. 2). In particular, the very high stemflow from the peachpalms overcompensated by far for the second lowest throughfall values observed in the plots. During stronger rainfall events, dozens of liters of stemflow poured down from single fruit palms, and the highest quantities measured during this study depassed 160 l from one palm individual in a single rain event. For peachpalm for palmito, the calculated water input near the plant depends on the number of offshoots producing significant amounts of stemflow. The plants usually had two, in some cases three offshoots, plus sometimes a few very small offshoots which produced little stemflow (see Fig. 4). Fig. 2 gives the water inputs for both cases. In the normal case with two offshoots, the immediate surroundings of a peachpalm for palmito appears as the driest place within a polyculture plot. This may be explained with rain interception in the leaf sheaths and some outward channelling of rain falling on the leaves, but there was certainly also a larger error in the stemflow measurements for this species in comparison to the others because the smooth surface of the offshoots made a water-proof attachment of the collars very difficult, and their fast growth caused frequent breaking of the collars and water leakage. So, total stemflow was almost certainly underestimated for this species. For cupuacu and urucum, the stemflow contributed very little to the total water input.

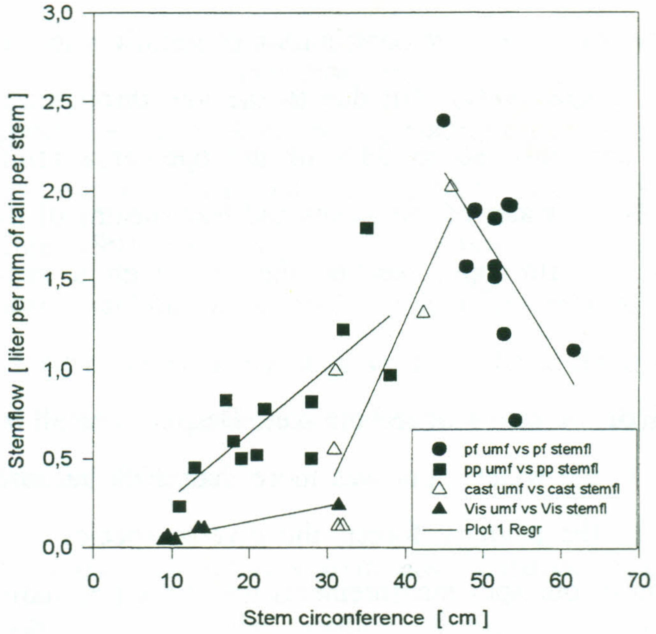

Figure 4: Relationship between stem circonference and stemflow for four of the investigated tree species. Each point corresponds to the total stemflow measured on an individual measurement tree during this experiment. For peachpalm for palmito, only events between March and June 1996 were included. The regression functions were for Brazil nut: stemflow = -2.58 + 0.0965 * circonference (r^2 = 0.76, $p < 0.05$); for peachpalm offshoots: stemflow = -0.088 + 0.0364 * circonference (r^2 = 0.57, $p < 0.01$); for *Vismia*: stemflow = -0.026 + 0.00842 * circonference (r^2 = 0.96, $p < 0.001$); for peachpalm for fruit: stemflow = 5.32 – 0.0714 * circonference (r^2 = 0.42, $p < 0.05$).

Because of the close spacing of the trees in the peachpalm monocultures, it can be assumed that the whole ground area was affected to some extent by stemflow. The total amount of stemflow in the peachpalm for fruit plots is subject to error, because stemflow was not measured separately on the palmito palms in the understorey which would not be there in commercial plantations. So, we used the stemflow data from the palmito monocultures for estimating the total stemflow in the peachpalm for fruit monocultures. This may have resulted in an overestimation of total stemflow in these plots, because the understorey plants were normally smaller than the plants in the pure palmito plots and they were also partly shielded from incoming rain by the fruit palm overstorey.

Total water input per system

Tab. 4 summarises the throughfall and stemflow data for the whole plots. In the polyculture, only 3.4% of the incoming rain were transformed into stemflow, of which more than two thirds were produced by the palms. Throughfall summed up to 90.2% of the rain, giving a total water input of 93.5%. The remaining 6.5% were lost by direct evaporation from the canopy (interception loss). In the peachpalm monocultures, the contribution of stemflow to total water input was much higher (24.7 and 20.6%, respectively), but due to the low throughfall values, the quantity of water reaching the soil was only 86 to 88% of the open-area rainfall. This illustrates the significant storage capacity for water of the leaves and leaf sheaths of the palms. In the cupuacu monoculture, 99.5% of the rain input reached the soil, with a negligeable contribution of stemflow.

In the fallow plots, 97% of the rain reached the soil. Despite a small water yield per stem, the contribution of stemflow to the water input was more than 20% because of the high number of stems per ground area. In the primary forest, the diverse species and size class composition prohibits the extrapolation of our spot measurements under six tree individuals from two species to an area beyond the immediate vicinity of the measured trees. Under *Eschweilera*, throughfall was similar to that in the fallow, but there was little stemflow, so that the total water input close to the stem was only 79% of the open-area rainfall. Under *Oenocarpus*, a higher throughfall and significant stemflow summed up to 119% of the open-area rainfall, again reflecting the different hydrological strategies of dicotyledoneous trees and palms.

Discussion and Conclusions

In the polyculture system, the measured throughfall and stemflow were surprisingly similar to values measured in a primary rainforest reserve (Reserva Ducke) at less than 10 km from our experimental site (throughfall 91%, stemflow 1.8%), despite the major differences in stand age, biomass and canopy structure between these vegetation types (Lloyd and Marques, 1988). These authors mention the major contribution of a palm species to the total stemflow measured, confirming our finding that the different strategies of palms and dicotyledoneous trees with respect to rain interception and distribution lead to clear spatial patterns of water input into the soil even where the trees are part of a dense and heterogeneous forest canopy. The interception losses measured in our palm monocultures were higher than those in the Ducke reserve, whereas those of the fallow were lower. Total stemflow was much higher in both palm monocultures and fallow than in the forest reserve, in the first case because of the dominance of the palms, and in the second case because of the large number of stems per unit area. The latter case parallels to some extent the situation reported by Jordan (1978) from two rainforest sites in the Venezuelan Amazon, where the higher stemflow (7% as compared to 2% of total rainfall) was measured at the site with the higher number of small trees (< 10 cm) which contributed more than 80% to the total stemflow.

Few data on stand hydrology are available from tropical tree crop plantations. Imbach et al. (1989) measured interception losses of 14 to 16% in mature cacao plantations with shade trees in Costa Rica, but stemflow was not measured and the real values may have consequently been somewhat lower. Opakunle (1991) measured 2% of stemflow in an unshaded cacao plantation in Nigeria. These data indicate that both throughfall and stemflow may be lower in these plantations than in our polyculture system, presumably because in the latter the ground was not completely covered by the trees, and because there were no palms in the cacao plantations which contributed so significantly to stemflow in our study.

The characteristic feature of our polyculture system was the distinct spatial pattern of throughfall and stemflow which was related to the position of the tree species with their differing hydrological strategies (Fig. 2). Close to the stems of the palms and the Brazil nut trees, there were spots with strongly increased water input, surrounded by areas with reduced water availability due to rain interception by the crowns of the trees. All of the investigated tree species suppressed the ground vegetation approximately within the first 50 cm around the stem, presumably through shading and root competition in combination with the periodic slashing of the *Pueraria* when it climbed the trees. For Brazil nut, the area with sparse ground vegetation could even extend to several meters. The collection of rainfall from the area covered by the crown of a tree and its concentration near the own stem might give these trees a certain competitive advantage with respect to the ground vegetation in the acquisition of rain water and the nutrients it contains, including those leached from the respective tree itself. The importance of competition for water would presumably increase with the length and intensity of the dry season, but even in a relatively humid region such as central Amazonia, some tree species show symptoms of water deficiency during the dry months.

As mentioned initially, the increased water infiltration in the proximity of the stem of a tree species with high stemflow may also be a disadvantage. As in tree crop plantations, fertiliser is usually applied to the individual trees, there is a periodical overlap of zones of high infiltration with zones of high nutrient availability, so that fertiliser nutrients applied to palms or dicotyledoneous trees with high stemflow may be at a particular risk of being lost from the system by deep leaching. This could especially be the case when soluble fertilisers are applied in too high quantities at a time or out of synchrony with nutrient uptake by the crops. Unfortunately, very little is known about the actual nutrient requirements of tree crops under Amazonian conditions, with respect to both quantities and timing. From our experiment, there is evidence for significant leaching of fertiliser nutrients under the investigated tree species (Schroth et al., in preparation). Our data indicate that within the polyculture, soluble fertilisers should not be applied directly at the foot of the fruit palms and the Brazil nut trees, but should preferably be distributed in bands along the palm rows or around the individual trees with approximately 1 m distance from the stems. In the fruit palm monocultures, the fertiliser should be applied in the middle between the trees rather than around the individual trees. For urucum, cupuacu and peachpalm for palmito, on the other hand, there would be little risk that stemflow increases nutrient leaching.

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