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Single-tree effects in agroforestry with perennial crops - an approach to the optimisation of tropical land use systems

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ABSTRACT

The concept of single-tree effects has been developed in forest ecology by studying gradients of soil characteristics around individual trees which provide information about the specific influence which a tree of a certain species, age and size exerts on soil properties. We analyzed single-tree effects of useful tree species with the objective of characterizing the ecological role that a species plays when it is included in man-made ecosystems as a function of its morphological and physiological properties as modified by species interactions and management practices. We hypothesize that the understanding of such species-specific roles can help in optimizing agroforestry and other land use systems according to pre-defined objectives, such as the minimization of nutrient leaching, increase of chemical or physical soil fertility, high carbon accumulation in vegetation and soil etc. We measured the small-scale patterns of above- and belowground biomass and nutrient accumulation, root distribution, soil fertility, soil solution composition, quantity and nutrient concentration of rainwater, throughfall and stemflow, soil hydrology, soil physics and microclimate, among other variables, in a number of man-made and natural vegetation systems of differing structure and composition during two years. These included a polycultural system with *Bactris gasipaes, Theobroma grandiflorum, Bixa orellana, Bertholletia excelsa* and *Pueraria phaseoloides* at two fertilization levels; three monocultures with *Bactris gasipaes* either for fruit or palmito and *Theobroma grandiflorum*; a young fallow dominated by *Vismia* spp. and primary rainforest. The measurements produced evidence for differences of agronomic significance between the investigated plant species and cropping systems at numerous levels, including biomass accumulation, root distribution and soil fertility. Two examples for ecologically and agronomically significant single-tree effects are briefly discussed, with special emphasis on the practical recommendations which can be derived from this type of information: stand hydrology, and accumulation of mineral nitrogen in the subsoil.

RESUMO

O conceito dos efeitos de árvores individuais têm sido desenvolvido em ecologia florestal pelo estudo das características de gradientes ao redor de árvores individuais que fornecem informações sobre a influência específica que uma árvore de uma determinada espécie, idade e tamanho exerce sobre as propriedades do solo. Nós analisamos os efeitos de árvores individuais de valor comercial, com objetivo de caracterizar o papel ecológico que uma espécie desempenha quando ela está incluída em ecossistemas formados pelo homem como uma função de suas propriedades morfológicas e fisiológicas quando modificadas pela interação de espécies e práticas de manejo. A nossa hipótese é de que a compreensão do papel de tais espécies específicas possa ajudar na melhoria de sistemas agroflorestais e outros sistemas de usos de terra de acordo com objetivos pré-definidos, como a de minimização da lixiviação de nutrientes, aumento da fertilidade química e melhoria física do solo, maior acúmulo de carbono na vegetação, no solo etc. Nós medimos estruturas em pequena escala da biomassa acima e abaixo do perfil, acúmulo de nutrientes, distribuição de raízes, fertilidade do solo, composição da solução do solo, quantificação e concentração da água da chuva, escoamento de água na copa e no tronco, hidrologia do solo, física do solo, microclima e outras variáveis, em alguns sistemas de vegetação natural e feito pelo homem de diferente estrutura e composição durante dois anos. Estes, incluíram um sistema de policultivo com *Bactris gasipaes, Theobroma grandiflorum, Bixa orellana, Bertholletia excelsa* e *Pueraria phaseoloides* em dois níveis de fertilização; três monocultivos com *Bactris gasipaes* tanto para fruto quanto para palmito e *Theobroma grandiflorum*; uma capoeira jovem dominada por *Vismia* spp. e uma área de floresta primária. As medidas evidenciaram diferenças agronômicas significativas entre as epécies de plantas estudadas e os sistemas de cultivo em numerosos níveis, incluindo acúmulo de biomassa, distribuição de raízes e fertilidade do solo. Dois exemplos de efeitos de árvores individuais agronômica e ecologicamente significativos são discutidos resumidamente, com especial ênfase nas recomendações práticas que possam ser derivadas desse tipo de informação: hidrologia do dossel e acúmulo de nitrogênio no subsolo.

ZUSAMMENFASSUNG

Das Konzept der Einzelbaumeffekte ist in der Forstökologie entwickelt worden, basierend auf der Untersuchung von Gradienten in Bodeneigenschaften in der Umgebung einzelner Bäume, die Informationen bezüglich der spezifischen Wirkung von Bäumen abhängig von Art, Alter und Größe auf Bodeneigenschaften geben. Wir untersuchten Einzelbaumeffekte von Nutzbäumen mit dem Ziel, die ökologische Rolle zu charakterisieren, die eine Art spielt wenn sie in anthropogene Ökosysteme integriert wird. Diese sind durch die jeweiligen morphologischen und physiologischen Eigenschaften der Art bedingt und durch Interaktionen zwischen assoziierten Arten und Managementmaßnahmen modifiziert. Unsere Hypothese ist, daß das Verständnis solcher artspezifischer Rollen dabei helfen kann, agroforstliche und andere Landnutzungssysteme im Hinblick auf vorab definierte Ziele zu optimieren. Beispiele für solche Ziele sind die Verminderung von Nährstoffauswaschung, Erhöhung der physikalischen oder chemischen Bodenfruchtbarkeit, hohe Kohlenstoffakkumulation in Vegetation und Boden etc. Wir maßen die kleinräumigen Muster der ober- und unterirdischen Biomasse- und Nährstoffakkumulation, Wurzelverteilung, Bodenfruchtbarkeit, Zusammensetzung der Bodenlösung, Menge und Zusammensetzung von Regenwasser, Kronentraufe und Stammabfluß, Bodenhydrologie, Bodenphysik, Mikroklima und andere Variablen in mehreren anthropogenen und natürlichen Vegetationssystemen unterschiedlicher Struktur und Zusammensetzung über zwei Jahre. Die folgenden Systeme wurden untersucht: Ein Polykultursystem mit *Bactris gasipaes, Theobroma grandiflorum, Bixa orellana, Bertholletia excelsa* und *Pueraria phaseoloides* in zwei Düngungsstufen; drei Monokulturen mit *Bactris gasipaes* für Frucht oder für Palmherzen und *Theobroma grandiflorum*; eine junge Brache dominiert von *Vismia* spp. und Primärwald. In den Messungen wurden agronomisch signifikante Unterschiede zwischen den untersuchten Pflanzenarten und Anbausystemen auf zahlreichen Ebenen nachgewiesen, einschließlich Biomasseakkumulation, Wurzelverteilung und Bodenfruchtbarkeit. Zwei Beispiele für ökologisch und agronomisch wesentliche Einzelbaumeffekte werden kurz diskutiert, wobei die Betonung auf praktischen

Empfehlungen liegt, die aus dieser Art von Information abgeleitet werden können: Bestandeshydrologie und die Akkumulation von mineralischem Stickstoff im Unterboden.

INTRODUCTION

Agroforestry systems are mixtures of different plant and sometimes animal species, which differ in their life histories, their management and sometimes site requirements for optimum development and yield as well as their effects on the biotic and abiotic environment. The behavior of the system as a whole depends on the behavior of its component species as determined by their genetic properties and their interactions with site factors, associated species and management. So, when the interactions of such complex systems with environmental parameters, such as soil fertility or microclimate, are measured in field experiments, the results may be very specific for a given combination of plant (and animal) species, their spatial arrangement and their respective management chosen more or less subjectively by the experimenter. When the tested system is transferred into a farmer's field, many results from the previous experimentation may loose their validity, because the farmer may substitute some species by others, or he may modify their arrangement and management according to his needs and preferences. If, on the other hand, the potential components of agroforestry systems, i.e. the respective plant and animal species, are studied individually and in isolation, it may be very hard to predict their later behavior within the association, and consequently the behavior of the agroforestry system as a whole, due to the large number of possible interactions between the associated species.

A compromise between these two approaches, the study of whole systems and of isolated systems components, would be to analyze the individual roles of the systems components within the interaction and management context of a „best guess“ agroforestry system, with the objective of a stepwise optimization of the composition, design and management of the total system according to the specific biophysical and socioeconomic requirements of the respective situation. This would include the analysis of the effects that a certain plant (or animal) species has within the system with respect to soil fertility, microclimate, hydrology, nutrient cycling etc. and how these effects are related to characteristics of the plant and modified by associated plants and management measures. With such information, the system could then be optimized according to predefined objectives, such as minimum nutrient leaching, maximum carbon accumulation in the soil, maximum biodiversity of the soil or litter fauna etc. It is obvious that the validity of this approach depends heavily on the quality of the „best guess“ when designing the model agroforestry system, meaning the proximity of the system within which the component behavior and interactions are studied to the system which the farmer will later actually plant on his land.

Effects of individual plants (mostly trees) on their environment have been studied in forest ecosystems in the temperate zone (Zinke, 1962; Boettcher and Kalisz, 1990) and more recently in the tropics (Charpentier et al., 1995). These studies showed that even within dense and heterogeneous forest stands, the influence of tree species and individuals on soil properties including decomposer communities can be detected. However, within spontaneous vegetation systems, the question always remains if the specific properties of the soil in the surroundings of a certain tree are the consequence of its presence or rather the reason. A tree may have been able to establish at a certain place because of particularly suitable microsite conditions, and these may have little to do with the effect of the tree on the soil properties. With planted trees, this problem does not arise, provided appropriate randomization techniques have been used in setting up the experiment. In this case, significant relationships between environmental variables and the presence and characteristics of plant species can only be explained with an effect of the plant on the environment, and not the other way round.

A difficulty may arise in planted and managed systems such as agroforestry with the analysis of single-tree effects in so far as the specific effects of a species e.g. on soil and microclimate are determined both by the characteristics of the species itself (e.g. its root distribution, growth rate, crown shape etc.) and by the species-specific management that it receives, such as its fertilization rate, pruning treatments or harvest methods, and these two complexes can not be separated. It could be argued that this distinction is not necessary because in an agricultural or agroforestry system, every species comes together with its specific management so that it doesn't matter if a certain effect is caused by the species itself or by management practices that it requires. However, this argument is only valid when the management (e.g. the fertilization rate) has been specifically adapted to the respective species. If this is not the case, the effect of an inappropriate management can erroneously be taken as the effect of the species itself. This very important point will be illustrated below.

In the following, we present two examples of the analysis of single-tree effects in polyculture plantations in central Amazonia, with special emphasis on the practical recommendations which can be derived from this type of information. These examples are part of a more comprehensive study of plant and soil related processes in polyculture and monoculture plantations in central Amazonia.

MATERIAL AND METHODS

The study was conducted on the research station of EMBRAPA Amazônia Ocidental near Manaus in the Brazilian Amazon region (3° 8' S, 59°52' W, 40-50 m a.s.l.). The climate is of the Köppen Am type with an annual precipitation of 2622 mm, air temperature of 26°C and atmospheric humidity around 85% (mean values 1971-93, O.M.R. Cabral and C. Doza, unpublished). The driest months are July to September, and the wettest months are February to April. The soil is a Xanthic Ferralsol according to the FAO/Unesco classification with a clay content of about 80%. The study site was cleared from primary rainforest in 1980. In 1981, an experiment with rubber trees (*Hevea brasiliensis*) was established, which was abandoned in 1986. The developing secondary forest was manually cleared in 1992 and the vegetation was burnt on the site. The experimental plots were planted in the rainy season 1992/93.

The centerpiece of the study was a polyculture system with four locally important tree crop species: peachpalm (*Bactris gasipaes*, Arecaceae) for the production of fruits and of heart of palm (palmito), cupuaçu (*Theobroma grandiflorum*, Sterculiaceae), the Brazil nut tree (*Bertholletia excelsa,* Lecythidaceae) and urucum (*Bixa orellana*, Bixaceae). Plot size was 32 by 48 m. The trees were grown in rows with 4 m spacing between the rows. A row with peachpalm (at 2 m spacing within the row) alternated with a mixed row of cupuaçu and Brazil nut (at 6.7 m spacing between the trees within the row), a row of urucum (at 4 m spacing within the row) and again a mixed row of cupuaçu and Brazil nut, after which the next row of peachpalm followed. Between the trees, *Pueraria phaseoloides* (tropical kudzu, Fabaceae) was sown as a cover crop or developed from residual seed from the former rubber plantation. This system was studied at two fertilization levels, full fertilization according to local experiences and 30 % of this fertilization level. The low input plots received no N fertilizer since May 1996. For comparison, a peachpalm monoculture was included in the study, which was planted at 2 by 2 m and fertilized at the same rate per tree as the peachpalm in the polyculture plots with full fertilization. Also included were spontaneous fallow plots dominated by *Vismia* sp. The plots were arranged in a randomized complete block design with three replications (two further replications were not included in the study because of different site history and relief).

Stemflow and throughfall were collected under one tree individual per species and plot (two individuals per plot in the fallow and the monocultures). The values were summed up over one year for the data analysis. For the mineral nitrogen measurements, soil samples were collected until 2 m soil depth in October/November 1997, at the end of the dry season, at 50 cm from the trunk of one tree individual per species and plot. The mineral nitrogen was extracted by shaking with 1 M KCl solution and measuring ammonium and nitrate on a segmented flow analyzer.

The statistical analysis of the polyculture data was conducted by analysis of variance for a randomized complete block/split block design with the input levels as the main plot factor and the plant species as the split block factor. In case of significance of the F-test at $p < 0.05$, species means were compared by Least Significant Difference or Duncan's Multiple Range tests.

RESULTS AND DISCUSSION

Stand hydrology

Throughfall and stemflow within the agroforestry system depended significantly on the tree species under which they were measured (Table 1). Average throughfall at 40 cm from the stem ranged from less than 50 % of the open-area rainfall under peachpalm for palmito to over 100 % under urucum and Brazil nut. Stemflow ranged from more than 1 liter per mm of rain for peachpalm for fruit to very low values for urucum and cupuaçu. Some of the peachpalm and Brazil nut trees yielded more than 100 l of stemflow during single rainstorms. For the whole system, stemflow was 3.4 %, throughfall was 90.2 %, and interception loss was 6.4 % of the open-area rainfall. For comparison, the peachpalm for palmito monoculture had 20.6 % stemflow, 67.1 % throughfall and 12.3 % interception loss. The *Vismia* fallow had 20.3 % stemflow, 76.6 % throughfall and 3.1 % interception loss.

The striking feature of the polyculture system was the distinct spatial pattern of throughfall and stemflow which was related to the differing hydrological strategies of the tree species. 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 within the first 50 cm or so 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. So, 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 in the acquisition of rain water and the nutrients it contains, including those leached from the respective tree itself, with respect to the ground vegetation.

Table 1: Throughfall and stemflow measured under five tree species and at spots without trees (Pueraria) in an agroforestry system in central Amazonia during one year. Values within columns followed by the same letter are not different at $p < 0.05$ by Duncan's Multiple Range test.

Species	Throughfall 40 cm	Throughfall 150 cm	Stemflow liter mm^{-1}	Stemflow %	Throughfall+Stem-flow near stem
	% of the open	% of the open			% of the open
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
Cupuaçu	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

However, ecologically more important might be the increased water infiltration in the proximity of the stems of the tree species with high stemflow (Tanaka et al., 1996). In tree crop plantations, fertilizer is usually applied to the individual trees. There is consequently a periodical overlap of zones of high infiltration with zones of high nutrient availability, so that fertilizer 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, which means that soluble fertilizers should not be applied directly at the stem of these species. This recommendation, which may help to reduce unproductive fertilizer losses, would apply to the fruit palms and the Brazil nut trees (Table 1).

Mineral nitrogen distribution in the soil

The water input into a vegetation system and its redistribution when passing through the canopy and infiltrating into the soil is one factor which influences the fluxes of nutrients in the soil. Other factors are litterfall and mineralization, nutrient uptake by the plants, release of fixed nitrogen by legumes and fertilization. Because of the high mobility of nitrate in most soils and the correlation between nitrate fluxes and the fluxes of accompanying cations (e.g. Ca, Mg), the movements of mineral nitrogen in the soil are a sensitive and easily measured indicator for soil nutrient fluxes, and hence for the influence of plant species on these fluxes. Moreover, nitrogen fertilizers are expensive, and nitrogen losses through leaching can be an important negative-factor in the household economy.

Table 2 shows that at the end of the dry season in 1997, the top 2 m of soil under the investigated tree species in the polyculture contained considerable amounts of mineral nitrogen, mostly in the form of nitrate. From a simple average of the sampling positions within the plots, the total amount of mineral nitrogen per ha and 2 m soil was estimated as 315 kg in the fully fertilized polyculture, 260 kg in the 30 % fertilized polyculture, and 300 kg in the peachpalm for palmito monoculture (differences not significant). The mineral nitrogen stocks in the *Vismia* fallow were significantly lower with only 75 kg per ha, indicating that the main sources of this nitrogen were mineral fertilizer and biological nitrogen fixation by the leguminous cover crop, *Pueraria phaseoloides*. These were apparently leached out of the main rooting zone of the trees as indicated by the nitrate accumulations in the lower half of the investigated profiles under all species.

Table 2: Mineral nitrogen in the soil under four different tree crop species and a leguminous cover crop in a polyculture system on a ferralitic upland soil in central Amazonia at the end of the dry season 1997 (means of full and 30% fertilization, 0-2 m depth). Numbers followed by similar letters are not significantly different at $p < 0.05$ (LSD test). The effects of the fertilization level and the fertilizer-species interactions were not significant. The fallow data were not included in this test.

	Nitrate-N [g m^{-2}]	Ammonium-N [g m^{-2}]	Mineral N [g m^{-2}]
Peachpalm (palmito)	20.4 b	1.5	22.0 b
Cupuaçu	37.7 a	1.7	39.5 a
Brazil nut	18.7 b	1.8	20.6 b
Urucum	20.1 b	1.9	22.1 b
Pueraria	37.6 a	2.2	39.8 a
Fallow	5.9	1.6	7.5

Within the polyculture plots, the nitrogen was not equally distributed between the plant species. As for crown hydrology, single-tree influences were again detected with respect to the soil nitrogen status, with significantly higher values under cupuaçu and *Pueraria* than under the other three tree species, peachpalm, Brazil nut and urucum (Table 2). This indicates that, although nitrogen was lost into the subsoil by all species, the highest losses occurred under the tree crop cupuaçu and under the cover crop *Pueraria.* In the first case, this was presumably due to the inability of the tree to absorb the applied fertilizer nitrogen before it was leached, and in the second case the reason was most likely the surplus nitrogen from biological fixation which was released into the soil from decomposing plant material and was apparently not taken up by either the cover crop or the tree crops.

These results indicate that there is a potential for the optimization of the polyculture system, both at the level of the individual species and at the level of the systems design. With regard to cupuaçu (and, to a lesser extent, all the other tree species), fertilizer rates and especially the timing of the fertilization and the splitting of large fertilizer doses into smaller quantities need to be optimized in order to reduce leaching losses of nitrogen and accompanying cations. From the data in Table 2 it can however not be concluded that nitrogen losses will always be high under cupuaçu, but possibly only that the fertilization of this species was still less adapted to the requirements of this species than for the other tree crops in the experiment. With regard to the nitrogen losses under *Pueraria*, it appears that the design of the system should be modified in a way that allows the trees to make better use of the nitrogen under the cover crop. This would include lower nitrogen fertilization of the trees themselves, closer spacing and possibly the distribution of fertilizer on a wider circle around the trees in order to encourage lateral tree root development.

CONCLUSIONS

The presented examples confirm the hypotheses that perennial polycultures consist of a mosaic of situations with respect to soil-plant relationships, and that the analysis of these situations can lead to practical conclusions and recommendations with respect to the improvement of systems design and management. Of particular relevance for the Amazon region and many other tropical regions is a sound management of the fertility of soils under agriculture. For this, an efficient use of nutrients is essential. We have demonstrated how tree species differ in characteristics which are related to nutrient cycling and use. It is important that in the future such species characteristics as modified by interactions between associated species and management practices are taken into consideration when designing polyculture systems.

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