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Effects of tree clumps on soil characteristics in a humid savanna of West Africa (Lamto, Côte d'Ivoire)

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Abstract

The effect of tree clumps on soil characteristics was investigated in a humid savanna (Lamto, Côte d'Ivoire). Soil texture and field capacity were not significantly different under tree clumps compared to open grassland. On the other hand, bulk density was lower under tree clumps, likely due to a greater soil fauna activity under the trees. The pH, available phosphorus, cation exchange capacity, total carbon and total nitrogen contents were higher under tree clumps due to greater organic matter input beneath canopies. Potential soil respiration and mineral nitrogen accumulation were also enhanced, indicating a higher potential microbial activity under tree clumps. Soil water content was slightly lower beneath canopies (from July to November only between 0 and 10 cm depth) when soil moisture was above field capacity. During the other months, no significant difference was measured.

Introduction

Savannas are characterized by the cooccurence of a continuous herbaceous layer and a more or less discontinuous tree layer (Menaut, 1983). Both periodic water shortage (Goldstein and Sarmiento, 1987; Knoop and Walker, 1985) and low soil nutrient content (Bate and Gunton, 1982; Bell, 1982) have been considered as the major limiting factor for biomass production in savanna. Negative effects of tree clumps on the herbaceous layer could be reduced by a space partitioning in the soil, grass roots being mostly located in the topsoil, whereas tree roots are likely to be more widespread in the subsoil (Walter, 1971). Moreover, trees have often been reported to improve soil resources under their canopies (Bernhard-Reversat, 1982; Dancette and Poulain, 1969; Isichei and Muoghalu, 1992; Kellman, 1979), and to have beneficial effects on the herbaceous layer (Belsky et al., 1989; Weltzin and Coughenour, 1990). Improvement of soil fertility by trees constitutes one of the fundamental features of tree-grass relationships, among shading by tree canopies, protection from fire and increased tree seedlings recruitment (Menaut et al., 1990). Such a process might condition the overall savanna functioning, especially when considering its regeneration and stability/resilience properties (Frost et al., 1986).

The aim of the study was to determine if tree clumps in a humid savanna alter soil characteristics beneath their canopy compared to the open grassland. Several soil parameters (particle size distribution, bulk density, field capacity, pH, available phosphorus, cation exchange capacity, total carbon and total nitrogen) and soil resource attributes (soil respiration and accumulation of mineral nitrogen, soil water content dynamics) were measured in both situations.

Study area

The study was conducted in a humid savanna, at the Tropical Ecology Station of Lamto, Côte d'Ivoire (6°13′N, 5°02′W). Mean monthly temperatures are constant throughout the year (ca. 27°C) and rainfall averages 1200 mm yr^{-1} (Lamotte and Tireford, 1988). Soils are ferralsol (according to the FAO classification). The herbaceous layer is continuous and made of perennial tufted grasses. The aboveground parts are burnt by bush fire, each year in the middle of the dry season (January). Tree density varies along the catena, from almost pure grassland in bottomlands to dense shrub facies on plateaus. Total net production in the dense shrub facies for aboveground and belowground parts is respectively 16.1 and 10.4 Mg ha^{-1} yr^{-1} for the herbs, 2.8 and 0.2 for woody species (Menaut and César, 1979). Trees are mostly gathered into clumps.

Material and methods

Twenty tree clumps were chosen for the whole study. They were composed of only three species: *Crossopteryx febrifuga*, *Bridelia ferruginea*, *Cussonia barteri*. Their canopy cover, total basal area and number of trees respectively averaged 84.90 m^2 (s.e. = 5.06), 0.39 m^2 (s.e. = 0.04) and 4.25 (s.e. = 0.33). Several key soil characteristics were determined in order to compare soil conditions under tree clumps and in the open: pH, particle size distribution, bulk density, field capacity, available phosphorus, cation exchange capacity, total carbon, total nitrogen. Soil respiration and nitrogen mineralisation were also measured during incubations in optimal conditions as a reliable assessment of potential microbial activity (Dommergues, 1960, 1968).

Soil samples were excavated in the rainy season (June 1989). The samples were taken in the grass root zone, at four depths (0–5, 5–10, 10–20, 20–30 cm) down to 30 cm, horizon in which 90% of grass roots are concentrated, but as far as possible from a grass tuft to avoid a significant rhizospheric effect (Abbadie and Lensi, 1990). They were air-dried and sieved at 2 mm.

The pH was measured in distilled water. Soil texture was determined as follows: soil particles were separated by sieving and sedimentation after dispersing the aggregates by sodium hexametaphosphate and ultrasonic treatment (Feller, 1979). Available phosphorus was measured using the Olsen method (carbonate extraction reagent). Cation exchange capacity was determined by the Metson method (ammonium acetate as exchange solution at pH 7). Bulk density was measured on soil samples excavated according to the small cylinders procedure (Duchaufour, 1965). Moisture content at field capacity was determined as the remaining water content in soil sample after centrifugation at 1000 *g*. Total carbon was analyzed using the Anne (1945) method (potassium dichromate oxidation and titration of dichromate remaining with ammonium fer II sulfate). Total nitrogen was measured by the Kjeldahl method (oxydation by sulfuric acid, liberation of ammonia by steam distillation in the presence of excess NaOH and titration with HCl using methyl red indicator) with a Kjeltec Auto Analyser 1030 apparatus (Tecator). Carbon and nitrogen potential mineralisation were determined as follows: 20 g of dry soil were placed in small bottles, rehumidified to 80% of field capacity and incubated in the dark at 28°C. Seven days after, a microvolume of the air in the bottle was removed with a syringe in order to measure CO_2 concentration by Gas Chromatography (DI200 Auto Analyser, Delsi-Nermag). Immediately, the soil sample was shaken with 60 mL of KCl 2*N* during 30 min. After filtration, ammonium concentration on the one hand and nitrates + nitrites concentration on the other hand, were measured spectrophotometrically (Skalar Analytical): ammonia, after chloration is transformed in 5-aminosalicylicate which gives a blue-green complex, after oxydation and reaction using salicylic acid and nitroprussiate, measured at 660 nm. Nitrates are reduced in nitrites through a cadmium column. Nitrites (originally present plus reduced nitrates), with sulfanilamid and naphtylethylenediamine dihydrochloride gives a pink diazo complex measured at 540 nm.

Soil water content was also measured between 0 and 30 cm, gravimetrically. Each monthly value is an average of 12 samples taken over the month.

Data were submitted to a two way analysis of variance (testing canopy and depth effects, and their interaction) using SAS. Scheffe's test was used to compare the means.

Results

Clay and silt contents did not significantly vary with depth down to 30 cm and were not significantly influenced by tree clumps (Table 1). Bulk densities were significantly lower under tree clumps than in the open for each depth, and increased with depth under the tree clumps. Field capacity did not vary, neither with depth, nor with canopy effect. In both conditions, the pH was slightly acid and progressively decreased with depth. However, the pH always remained higher under tree clumps than in the open. There was an effect of canopy and depth on available phosphorus and cation exchange capacity which were higher under tree clumps than in the open and decreased with depth. Total carbon content of the soil decreased with depth and was higher under tree clumps than in the open. Total nitrogen content of the soil also decreased with depth and for each depth was higher under tree clumps. The calculated C/N ratio was lower under tree clumps than in the open. These differences in carbon content, nitrogen content and C/N ratio diminished with depth.

For each depth down to 30 cm, the amount of carbon dioxide produced by soil microbial activity during incubation was significantly higher under tree clumps (Fig. 1). This potential activity decreased significantly with depth, but when compared two by two layers, potential activity was not always significantly different (e.g. between 0–5 and 5–10 cm layers, neither in the open nor under tree clumps). Ratios of carbon

Table 1. Means and standard errors of clay and silt contents (%), bulk density (g cm^{-3}), pH, field capacity (% dry weight), available phosphorus (mg kg^{-1}), cation exchange capacity (cmol+kg^{-1}), total organic carbon concentration (gC kg^{-1}dry soil), total nitrogen content (gN kg^{-1} dry soil) and C/N ratio for each depth, under tree clumps and in the open

	0–5 cm		5–10 cm		10–20 cm		20–30 cm	
	Canopy	Open	Canopy	Open	Canopy	Open	Canopy	Open
Clay content	5.18*	4.63*					7.22	5.83
(n = 4)	(1.62)	(0.88)					(2.04)	(1.17)
Silt content	15.05*	15.41*					14.24	14.43
(n = 4)	(0.64)	(0.59)					(0.69)	(0.49)
Bulk density	1.52*	1.62*			1.55	1.62	1.59	1.63
(n = 24)	(0.01)	(0.01)			(0.01)	(0.01)	(0.01)	(0.01)
pH	6.88	6.63	6.74	6.49	6.32	6.19	6.19	5.67
(n = 6)	(0.16)	(0.04)	(0.16)	(0.05)	(0.24)	(0.07)	(0.21)	(0.11)
Field capacity	8.38	8.78	8.43	9.13	8.14	7.82	8.06	8.13
(n = 2)	(0.08)	(0.13)	(0.13)	(0.78)	(0.14)	(0.03)	(0.01)	(0.10)
Phosphorus	6.33	4.83	5.00	4.33	3.33	3.17	2.67	2.17
(n = 6)	(0.33)	(0.31)	(0.37)	(0.49)	(0.21)	(0.17)	(0.33)	(0.17)
C.E.C.	4.27	3.40	4.13	3.37	3.22	2.92	2.87	2.82
(n = 6)	(0.33)	(0.24)	(0.30)	(0.29)	(0.30)	(0.22)	(0.22)	(0.19)
Total carbon	8.43	7.26	7.87	7.00	5.91	5.59	4.61	4.42
(n = 10)	(0.31)	(0.24)	(0.29)	(0.31)	(0.28)	(0.25)	(0.23)	(0.19)
Total nitrogen	0.66	0.46	0.60	0.44	0.49	0.37	0.36	0.30
(n = 24)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
C/N ratio	12.77	15.78	13.12	15.91	12.06	15.11	12.81	14.73

* For 0–10 cm layer.

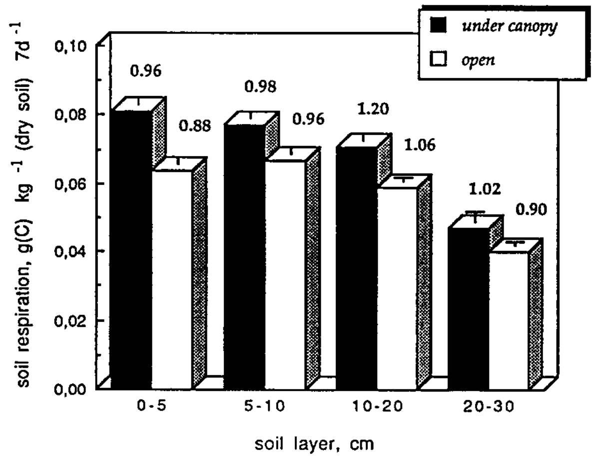

Fig. 1. Potential soil respiration after seven days of incubation (soil moisture: 80% of field capacity; temperature: 28°C) under tree clumps and in the open (n = 18); standard errors are indicated. The ratio of carbon mineralisation, expressed as % of total organic carbon in the soil, is mentioned above each column.

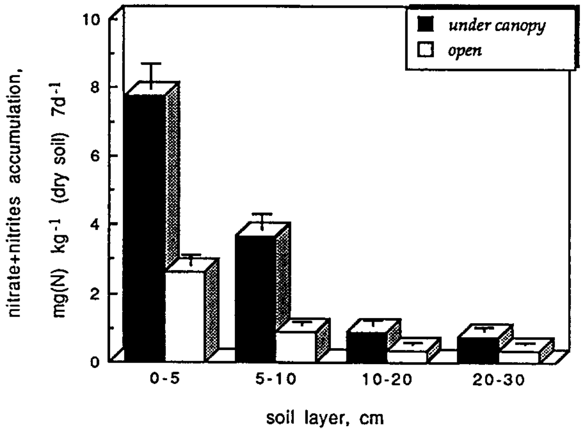

Fig. 3. Nitrates plus nitrites accumulation after seven days of incubation under tree clumps and in the open (n = 18).

mineralisation were calculated as carbon mineralised during seven days of incubation over total initial organic carbon (Dommergues, 1960). The ratios ranged from 0.88 to 1.20% (Fig. 1). They were slightly higher under tree clumps for each depth. For both situations the 10–20 cm layer showed the highest ratio. Potential accumulation of ammonium (Fig. 2) and nitrate/nitrite (Fig. 3) was higher under tree clumps than in the open for each layer (not significantly for ammonium in the 0–5 cm layer). Nitrate accumulation was far lower than ammonium accumulation. There was an overall decrease in mineral nitrogen accumulation with depth. Nevertheless, for two successive soil layers, the decrease was not always significant neither for ammonium nor nitrates in both situations, canopy or open.

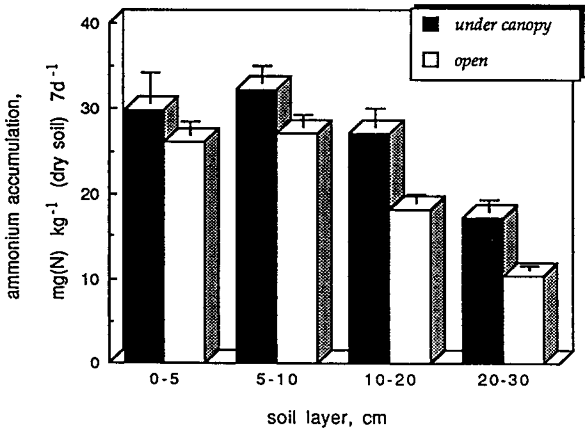

Fig. 2. Ammonium accumulation after seven days of incubation under tree clumps and in the open (n = 18).

Soil moisture dynamics remained comparable in all layers, although variations were smoothened in the deeper layers. A slight discrepancy occurred between both situations, when soil moisture was higher than field capacity, but it never went beyond 3% (of dry weight) above what was observed in the open (Fig. 4). The difference was significant from July to November between 0 and 10 cm, and in July-August between 10 and 30 cm. On the contrary, differences in soil moisture tended to disappear at the end of the dry season; however, in February 1990, soil moisture was significantly higher under tree clumps, between 0 and 10 cm soil depth (Fig. 5).

Discussion

Two soil characteristics only were not significantly modified beneath tree clumps: particle size distribution and field capacity.

Tree community dynamics are often shown to

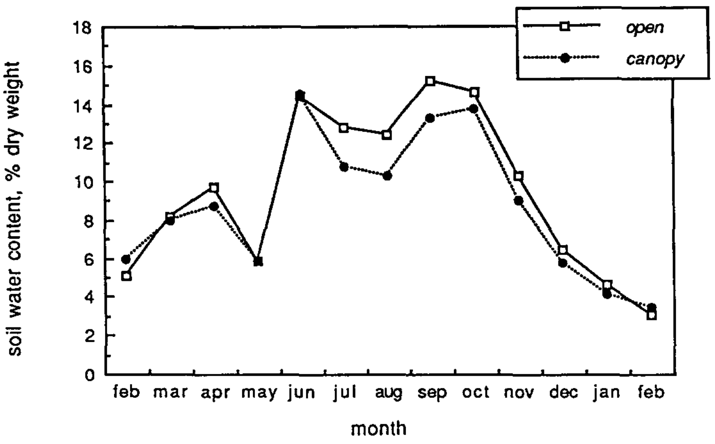

Fig. 4. Mean soil water content dynamics in the open and underneath canopy, averaged between 0 and 30 cm, from February 1989 to February 1990 (n = 48).

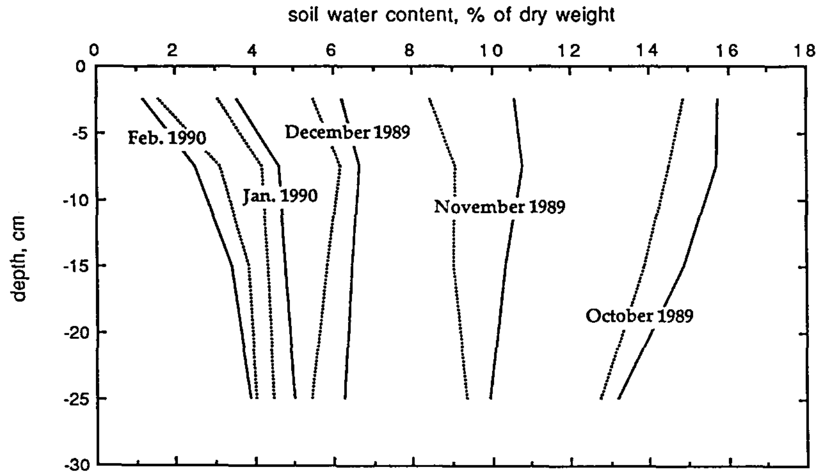

Fig. 5. Soil water content dynamics down to 30 cm depth, from October 1989 to February 1990, under tree clumps (dashed lines) and in the open (solid lines) (n = 12).

be associated to particular soil texture conditions (Ben-Shahar, 1991), preexisting or induced. In some situations, texture was supposed to be modified after tree settlement. For example, Isichei and Muoghalu (1992) claimed that it could come from an accumulation of aeolian material under tree canopies in Nigerian savannas. Most often, tree settlement seems to be favoured by particular preexisting soil physical conditions. This phenomenon was only observed in Lamto in those sites where many tree clumps grow on old termite mounds in which the clay content is higher than in the surrounding soil (Abbadie et al., 1992a). Anyhow, in our study area where termite mounds are rather rare, there is no obvious link between soil texture and tree occurrence. Particle size distribution was the same under tree clumps and in the open savanna; these results meet those published by Dancette and Poulain (1969) about *Acacia albida* savannas, where tree clump settlement was not promoted by particular soil texture conditions and, conversely, tree clumps settlement has not led to any change in soil texture.

Field capacity is closely related to silt and clay contents (Baize, 1988). Consequently, as soil texture remained constant, it was expected that field capacity would not differ between tree clumps and open areas. Tree clumps can modify soil water content dynamics as they act on both soil water inputs and outputs. Kessler and Breman (1991) have reviewed three field processes controlling moisture availability under woody species: rainfall interception, evapotranspiration and water infiltration. According to the level of each of these processes, tree canopy effects can lead to various, complex and contrasting situations. In Lamto, throughfall was 193 mm less than the incoming rainfall between April 1st, 1989 and January 31, 1990. Stemflow (unmeasured), could have alleviated the difference, but interception is likely to partly account for the observed discrepancy between soil moisture beneath the canopy and in the open: soil water content was slightly lower under tree clumps from July to November. But during this period it was always over field capacity, and hence without any negative consequence on plant growth. As far as soil fertility is concerned, soil moisture controls soil nutrient status, in the long term by the rate of pedogenic processes, and in the short term through nutrient availability (Scholes, 1987). Particularly, soil moisture controls microbial activity, i.e. nutrient release, and water infiltration leads to a redistribution of nutrients in the soil. Since no important differences were observed in soil water dynamics between 'canopy' and 'open', it cannot contribute to explain differences in soil nutrient status.

Some other soil characteristics were modified beneath tree clumps: cation exchange capacity, pH, available phosphorus, total carbon, total nitrogen, soil respiration and mineral nitrogen accumulation, bulk density.

A bulk density lower under trees than in the open has already been observed by Belsky et al. (1989) in Kenya. Bulk density is inversely related to soil porosity which depends on soil texture and soil structure. In Lamto, since soil texture was the same under tree clumps and in the open, it cannot account for the observed differences in bulk density. Roots, being of much lower density than soil and leaving often channels in the soil after their death, could contribute to lower bulk density. But, the difference in root phytomass in both situations for the 0–10 cm layer, where the difference of bulk density is maximum, cannot account for any significant variation in bulk density. Such variations might come from the activity of the soil fauna: earthworms and termites are known to decrease soil bulk density. In savanna-like formations, Joffre (1987) showed that earthworms density was, under the trees, 5 times what it was in the open. In Lamto, termites also concentrate under tree clumps where they mostly feed on tree litter (Lepage 1983; Lepage et al., 1993). An increase in soil macroporosity under tree clumps is then most likely to depend on soil fauna activity.

Cation exchange capacity is known to be mainly linked to clay and organic matter contents. In the case of Lamto savanna, only the higher organic matter content and higher litter quality under tree clumps could account for the higher cation exchange capacity as clay content was not changed by tree settlement.

pH is closely related to soil organic matter and cation exchange capacity. It was higher under tree clumps in Lamto, as shown by Kennard and Walker (1973) in Southern African savannas. Among cations, calcium, in which tree litter is particularly rich, should play a major role (Dancette and Poulain, 1969; Drechsel et al., 1991).

In most studies available phosphorus is higher beneath tree canopy than in the open (Belsky et al., 1989; Isichei and Muoghalu, 1992). But under *Acacia albida* it is found higher in Zimbabwe (Dunham, 1991), and lower in Senegal (Dancette and Poulain, 1969). In Lamto, where the amount of available phosphorus was low, as already recorded by Delmas (1967), the difference between 'canopy' and 'open' is likely due to additional nutrient input by tree litter through tree leaf litter fall and not to pH variation.

Soil organic carbon content is positively correlated to soil texture, clay content particularly (Jones, 1973). Therefore, we could have expected no differences between total carbon content under tree clumps and in the open. However soil organic carbon not only depends on storage capacity but also on inputs. Higher total carbon (or organic matter) content is generally recorded beneath tree canopies (Dunham, 1991; Frost and Edinger, 1991; Isichei and Muoghalu, 1992; Jackson, 1990; Weltzin and Coughenour, 1990). Higher inputs under tree clumps may partly come from bird droppings, ungulate dungs (Belsky et al., 1989; Weltzin and Coughenour, 1990), or through-fall leachates from tree canopies (Isichei and Muoghalu, 1992; Kessler and Breman, 1991). However, leaf fall is considered to be the main input or organic matter under tree canopies. In Lamto shrub savanna, leaf fall ranges from 0.9 t ha^{-1} in open facies to 1.8 t ha^{-1} in dense facies (Menaut, 1974) and mainly occurs right under the trees. However, leaves fallen before fire occurs (the major part) are burnt and do not significantly account for the improvement in soil fertility. The most important input likely comes from the overall root phytomass which is greater under tree clumps (unpublished data). It could lead to an higher input of organic carbon to the soil, primarily from dead root humification and secondarily from root exudates.

Total organic nitrogen was greater under tree clumps, but the difference between 'canopy' and 'open' was higher than for total carbon. This led to a lower C/N ratio under tree clumps as observed in other studies (Ovalle and Avendaño, 1988). This diverging dynamics of C and N could be explained by the C/N differences in the organic matter originating from tree and grass material. In the open, organic matter mainly comes from grasses (Martin et al., 1990). Under tree clumps, a higher proportion of tree material, with a lower C/N ratio, contributes to soil organic matter which consequently should have a lower C/N ratio. However, the relative concentration of organic nitrogen under tree clumps could also be due to a higher microbial activity. Organic matter metabolism by microorganisms results in an irreversible release of carbon dioxide in the atmosphere and a mineral nitrogen production which is partly immobilized in the microbial biomass. Thus, the higher mineralisation is, the lower the C/N ratio becomes. Incubations in optimal conditions support this interpretation: microorganisms are more active and/or more numerous under tree clumps than in the open.

The higher microbial activity could be the result of the particular conditions prevailing under tree clumps:

1. Over the year, root phytomass is higher under tree clumps, so would be microfauna, especially termites. Both of them stimulate carbon and nitrogen mineralisation (Abbadie, 1990; Abbadie and Lepage, 1989).
2. Organic matter is of better quality under tree clumps (higher mineralisation ratio), likely because of a lower C/N ratio. It appears as a sort of autostimulation as C/N also depends on microbial activity.
3. Evidence was given that the dominant grass, *Hyparrhenia diplandra*, inhibits nitrification (Lensi et al., 1992; Meiklejohn, 1968). Since *Hyparrhenia diplandra* phytomass is lower under tree clumps (unpublished data) the inhibition could be lower and consequently, the microbial activity higher.
4. As far as total organic nitrogen is concentrated, mineral nitrogen accumulation is potentially greater.
5. Climatic conditions are more favourable under tree clumps. A lower bulk density means a greater porosity and then a better soil aeration, necessary for oxidizing microorganisms activity.

Conclusion

The non significantly different soil clay content under tree clumps as compared to open grassland is of primary importance because it provides informations on tree clumps dynamics. Tree clumps do not seem to settle in sites displaying special soil conditions. Once they have settled, tree clumps are able to improve soil fertility by enhancing mineralisation processes (microbial activity) and lowering bulk density (soil fauna activity). Thus, tree clumps do not deplete soil resources available to grass roots. On the opposite, tree architecture and physiology result in the concentration of nutrients in the topsoil beneath the canopy. Nutrients are uptaken by tree roots in a large volume of soil, partly incorporated in leaves which fall mainly beneath tree canopy where nutrients are released, leading to a concentration or organic carbon, total nitrogen, available phosphorus and cations in the topsoil under tree clumps.

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