Vertical root distribution in single-crop and intercropping agricultural systems in Central Kenya

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Abstract

Intercropping is an important and widespread land-management system in the tropics. At two agricultural sites in Central Kenya differing in elevation and soil type Haplic Nitisols (eutric) and Vitric Gleysols (eutric, epiclayic, endoclayic), we investigated the vertical root distributions using the trench wall profile method in single-crop systems of maize (*Zea mays* L.) and in intercropping systems of maize and legumes (common bean, *Phaseolus vulgaris* L.; pigeon pea, *Cajanus cajan* [L.] Millsp.) to test for possible differences in the use of water and nutrient resources. The physico-chemical soil properties of the sites were similar and imposed no restrictions to the vertical growth of the roots into soil depths of 1.4 m. The vertical distributions of the fine roots (∅ 0.5–2 mm) and very fine roots (∅ < 0.5 mm) were quantified by calculating the parameter β which was computed from the cumulative fraction (*Y*) of the root densities along the depth (*d*) of the soil profiles ($Y = 1 - \beta^d$). We found no consistent differences between the single-crop and the intercropping systems in the rooting depth down to 1.4 m. However, higher β values for fine roots of the intercropping systems were indicative of a more homogeneous vertical root distribution than in the single-crop fields. In the intercropping fields, 50% of the total number of fine roots were distributed over the uppermost 36 cm of the soil, whereas in the single-crop fields, 50% of the fine roots were concentrated in the uppermost 15–21 cm. Medium-sized roots (∅ > 2–5 mm) were detected in the intercropping fields only. The more homogeneous root distribution in the intercropping fields likely indicates a more efficient use of the limited resources nutrients and water.

Key words: cumulative root distribution / Mount Kenya / resource utilization / *Zea mays* / *Phaseolus vulgaris* / *Cajanus cajan*

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1 Introduction

In the tropics, intercropping land management is seen as one important technique to achieve a sustainable agriculture management (*Benzing*, 1995). Agronomic research is cumulatively confirming that the yield of crops grown in combination is greater than the sum of the yield of individual crops grown in monoculture on the same total land area (*e.g., Ghosh* et al., 2007). Another advantage of intercropping systems is the more efficient utilization of environmental resources, particularly irradiance (*Awal* et al., 2006) and soil water (*Rodrigo* et al., 2005), and—in some cases—reduced damage from pests and diseases (*Poveda* et al., 2008). In addition, the denser ground coverage by the plants may provide greater protection from soil erosion (*Zougmore* et al., 2000) and weed invasion (*van Mourik* et al., 2008). Intercropping also gives greater yield stability between years and among sites (*Norman* et al., 1995).

Whilst several studies have been conducted on the benefits of intercropping over single-crop systems with regard to yield, water use, and nutrient relations, the underlying mechanisms, especially the root distribution in the soils of those systems, have received much less attention, and knowledge is lacking (*Zhang* and *Li*, 2003). In a study conducted in the Andes Mountains of SW Colombia, higher root numbers were found in the soil of cassava fields (*Manihot esculenta* Crantz) when intercropped with the legumes *Centrosema acutifolium* Benth. or *Zornia glabra* Desv. (*Muhr* et al., 1995). This finding was indicative of a more complete exploitation of nutrient resources in the soil. In the sand-dominated semiarid region of N Namibia, the root-weight density of pearl millet (*Pennisetum glaucum*) was increased in deeper soil layers, and reduced in the uppermost soil layers when intercropped with cowpea (*Vigna unguiculata*) (*Zegada-Lizarazu* et al., 2006). For the clay-rich tropical regions of E Africa, studies on the vertical root distribution of intercropping *versus* single-crop systems containing the widespread and important maize (*Zea mays*) are nonexistent.

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The Mt. Kenya area comprises a variety of agroecological zones. Besides the moisture supply, which is the main factor for the classification of agro-climatic zones in the tropics, the elevation above sea level and the soil characteristics also play an important role in that region (*Jaetzold* and *Schmidt*, 1983). This differentiation provides a framework for the ecological land-use potential. The area of the present study is located in the lower, cultivated zone of Mt. Kenya with altitudes ranging from 1120 m to 2600 m asl. It is densely populated, which has resulted in a continuous cultivation of land with increasing pressure on the landscape.

Throughout the tropics and in Central Kenya in particular, rain-fed cereals such as maize can be found growing as a component of mixed and intercropping patterns. In addition to annual crops and vegetables, some few perennial fruit and nut trees are grown (*Norman* et al., 1995). In the Mt. Kenya region, however, the dominating land-management system relies on single crops, predominantly on maize. The advantage of cereals over noncereal energy crops, such as root and tuber crops or bananas, is the short cropping period. A disadvantage of growing maize in the tropics is the low yield caused by the species' sensitivity to drought stress and supraoptimal temperature. Maize is particularly sensitive to water deficit at flowering (*Salter* and *Goode*, 1967). Drought reduces the leaf area, leaf photosynthetic rate, and grain number (*Hall* et al., 1980). Therefore, the question arises whether intercropping results in a more intense, but also in a more homogeneous penetration of the soil by the roots. This would be a prerequisite for a larger extent of resource exploitation.

The present study focuses on the vertical root distribution of single-crop and intercropping agricultural systems in the watershed area Ngaciuma-Kinyaritha of the Mt. Kenya region. We hypothesized that in the maize intercropping systems, (1) fine roots penetrate deeper into the soil, (2) the coverage by fine roots is more intense, and (3) fine roots are distributed more homogeneously along the vertical soil profile than in maize monocultures. The latter hypothesis was derived from the expectation that different crops exhibit different rooting patterns, which allow for occupying different spaces in the soil. In this case, the entire rooting volume would be penetrated more homogeneously. To test these hypotheses, study sites were selected in contrasting elevations and on different soil types. The results of the study are intended to contribute to the development of productive and sustainable management strategies for the agricultural systems in the densely populated piedmont of Mt. Kenya.

2 Materials and methods

2.1 Study sites

The study was performed at four sites, two in the locality of Kithoka and two in the location of Thuura, in the Mt. Kenya region, Central Kenya.

Kithoka is located in the upper midland agro-ecological zone UM2 (*Jaetzold* and *Schmidt*, 1983), which is the principal coffee-growing zone. The climate is subhumid. The study sites were located on the crest of a plateau. Soils are Haplic Nitisols derived from pyroclastic tuff. Thuura is located in the Lower Midland agro-ecological Zone LM3, which is the cotton zone (*Jaetzold* and *Schmidt*, 1983). The climate is semihumid. The test sites were situated on an almost level area. The soils are Vitric Gleysols derived from fluvial sediments. Site characteristics are presented in Tab. 1.

At both locations, one site was an intercropping and one a single-crop culture. Land use is rain-fed arable cultivation with a year-round growing period with two cropping seasons. Maize (*Zea mays*) is the main crop. Within the cropping cycle, it is sown in the middle of October and harvested in March. At the time of the investigation in January 2009, the maize plants were three months old. Where intercropping was applied, legumes were seeded in alternation with one (Kithoka) or two (Thuura) rows of maize. Intercrops are mainly a black variety of common bean (*Phaseolus vulgaris* L.) and pigeon pea (*Cajanus cajan* [L.] Millsp.). The harvest

Table 1: Characteristics of the study sites in the Mt. Kenya region.

Study site	**Kithoka**		**Thuura**	
Cropping system	single crop	intercropping	single crop	intercropping
Location	0°07′8.641″ N 37°40′40.94″ E	0°07′6.393″ N 37°40′14.095″ E	0°03′53.766″ N 37°44′51.355″ E	0°03′54.287″ N 37°44′51.743″ E
Elevation	1457 m asl	1430 m asl	1159 m asl	1169 m asl
Annual mean temperature	18.2°C–20.6°C		20.6°C–22.9°C	
Annual available precipitation	1500–2400 mm		1500–2400 mm	
First rain (mid-March to May)	450–800 mm		300–600 mm	
Second rain (October to December)	450–800 mm		320–600 mm	
Soil parent material	Pyroclastic tuff		unconsolidated fluvial deposits (silt and clay)	
Soil type§	Haplic Nitisol (eutric)		Vitric Gleysol (eutric, epiclayic, endoclayic)	

§ according to WRB classification (*FAO*, 2006) of common bean is in January. The pigeon pea is a perennial crop and is being left in the fields after harvesting. Rotation of the fields is carried out in each season.

2.2 Leaf-area index and crop height

The leaf-area index (LAI) was determined by harvesting leaves from three replicate plots with a soil surface area of 1 m^2 within a row of maize at the single-crop sites and within a legume row at the intercropping sites in Kithoka and Thuura. The leaf area was measured with a portable area meter (LI-3000A; LI-COR, Lincoln, NE, USA). The LAI was computed by dividing the leaf area by the soil surface area. The height of the crops at the study sites was also measured.

2.3 Soil-chemical analyses

The soil-chemical analyses were performed in site-representative samples taken from different soil depths of the single-crop or intercropping sites. In Kithoka, the depths of sampling for single crop and intercropping were as follows: 0–20, 20–40, 40–60, 60–100, and > 100 cm. In Thuura, the sampling depths were also chosen in accordance with the natural soil and substrate characteristics: 0–10, 10–30, 30–60, 60–80, 80–100, and > 100 cm of soil depth at the single-crop site, and 0–30, 30–45, 45–80, 80–120, 120–140, and > 140 cm at the intercropping site.

All soil-chemical analyses were done in duplicate. The pH values of the soil samples were measured in a suspension of soil in 1 *M* KCl (1:2.5; v/v). The concentrations of organic C (C_{org}) and total N (N_t) were determined in dried (60°C, 24 h) and ground soil subsamples using an element analyzer (Elementar Vario El, Elementar, Hanau, Germany).

For the quantification of the effective cation-exchange capacity (ECEC), a mixture of air-dried soil and 1 *M* NH_4Cl (1:10; v/v) was shaken for 2 h and percolated. In the percolate, the concentrations of Ca, Mg, K, Na, Al, Fe, Mn, and Zn were determined *via* atomic absorption spectrometry (SpectrAA-30, Varian, Darmstadt, Germany and ContrAA 300, Analytik Jena, Jena, Germany). The ECEC was calculated as the sum of the ion equivalents of the metal cations listed above.

2.4 Soil-physical analyses

For the determination of the particle-size distribution, the pipette analysis according to Köhn (*Hartge* and *Horn*, 2009) was applied to air-dried soil substrate (particle size < 2 mm) of samples taken from the intercropping sites of Thuura and Kithoka. The classification of particle sizes followed the protocol of the *Ad-hoc Arbeitsgruppe Boden* (2005).

The soil bulk density was determined after drying the undisturbed soil samples at 105°C. The penetration resistance was measured in the undisturbed soil samples. For that purpose, a soil sample was put on a balance and the probe head of a drill rig was pressed into the soil up to a given mark. The reading in kilogram per head area was finally converted into pressure units. The air permeability of the soil was determined according to the method of *Kmoch* and *Hanus* (1965).

2.5 Vertical root distribution

The root investigations were performed in January 2009 using the trench wall profile method according to the FAO guidelines (*FAO*, 2006). One trench per location and cropping system was dug in parallel to the maize rows, 15 cm afar from the stalks, with dimensions that allowed for a site-representative determination of the vertical root distribution (trench width, 0.3 m; trench depth, 1.4 m); however, the maximum rooting depth could not be reached. In each trench, relevés were made in three vertical profiles that covered a width of 10 cm each. The diameters and the numbers of the roots were determined according to a root classification chart (*FAO*, 2006). In this classification, the roots are assigned to different size classes according to their diameters as follows: very fine roots (< 0.5 mm), fine roots (0.5 to 2 mm), medium roots (> 2 to 5 mm), and coarse roots (> 5 mm). Roots were counted in 4 cm × 4 cm grid cells. For further evaluation (see below), the root countings were recalculated by relating them to unit areas of 10 cm × 10 cm. Due to the similar visual appearance of all very fine and fine roots, individual roots could not be assigned to individual crop species.

2.6 Data analyses

In the evaluation of the data, we focused on roots of the fine and very fine size classes as their distribution is more important for resource acquisition than that of coarser roots (*Lauenroth* and *Gill*, 2003).

For each soil trench, average values of the densities of very fine and fine roots (number of roots per 10 cm × 10 cm of vertical soil surface area) were calculated from the three soil profiles per trench for 10 cm increments of soil depth. For each location of the study, these values were used for a trench-wise comparison of the single-crop and intercropping systems (Kolmogorov-Smirnov Two-Sample Test; PASW Statistics 17.0.2, SPSS Inc., Chicago, IL, USA; Wilcoxon Signed Rank Test; SigmaStat 3.5, Systat Software, Chicago, IL, USA). In addition, the cumulative vertical distribution of roots was trench-wise calculated from the average values of root density according to the model by *Gale* and *Grigal* (1987) as a measure of the heterogeneity of the vertical root distribution in the soil profiles:

$$Y = 1 - \beta^{d}, \qquad (1)$$

where Y is the cumulative root fraction from the soil surface to deeper soil layers (a proportion between 0 and 1), d is the soil depth (cm), and β is the fitted parameter. For each root-size class and study site, an average β value was calculated for the entire soil profile from the 10 cm increments of soil depth. Generally, β values range between 0.9 and 1.0. High values of β (close to 1.0) are associated with a larger fraction of roots at deeper soil horizons, whereas lower values of β (close to 0.9) are indicative of a more superficial root distribution. In case of marked differences among the β values, the

Table 2: Leaf-area index (LAI) and crop height of *Zea mays* at both single-crop sites, and of *Phaseolus vulgaris* and *Cajanus cajan* at both intercropping sites in Kithoka and Thuura (means ± 1 SE).

Kithoka		**Thuura**	
LAI / m^2 m^{-2}	height / m	LAI / m^2 m^{-2}	height / m
Zea mays			
2.44 ± 0.69	2.95 ± 0.30	1.00 ± 0.13	2.13 ± 0.06
Phaseolus vulgaris and *Cajanus cajan*			
1.05 ± 0.09	0.55 ± 0.06	0.88 ± 0.26	0.62 ± 0.04

slopes (log β) of the log-transformed Eq. 1 were tested for equality against the distribution of *F* values according to *Sokal* and *Rohlf* (1995).

3 Results

3.1 Leaf-area index and crop height

One hundred days after sowing, the maize was in the period of yield formation. At the same time, the beans were in their ripening period and thus not in the period of maximum LAI. In Kithoka, the LAI of maize was almost 2.5 times larger than in Thuura (Tab. 2). The maize stand in Thuura was affected by drought with many leaves being dry; their area was not included in the LAI. The maize stand in Kithoka was also higher than that in Thuura. For the legumes, the difference in LAI between Kithoka and Thuura did not exceed 0.17 and is regarded small. The space between the rows at the single-crop sites remained bare.

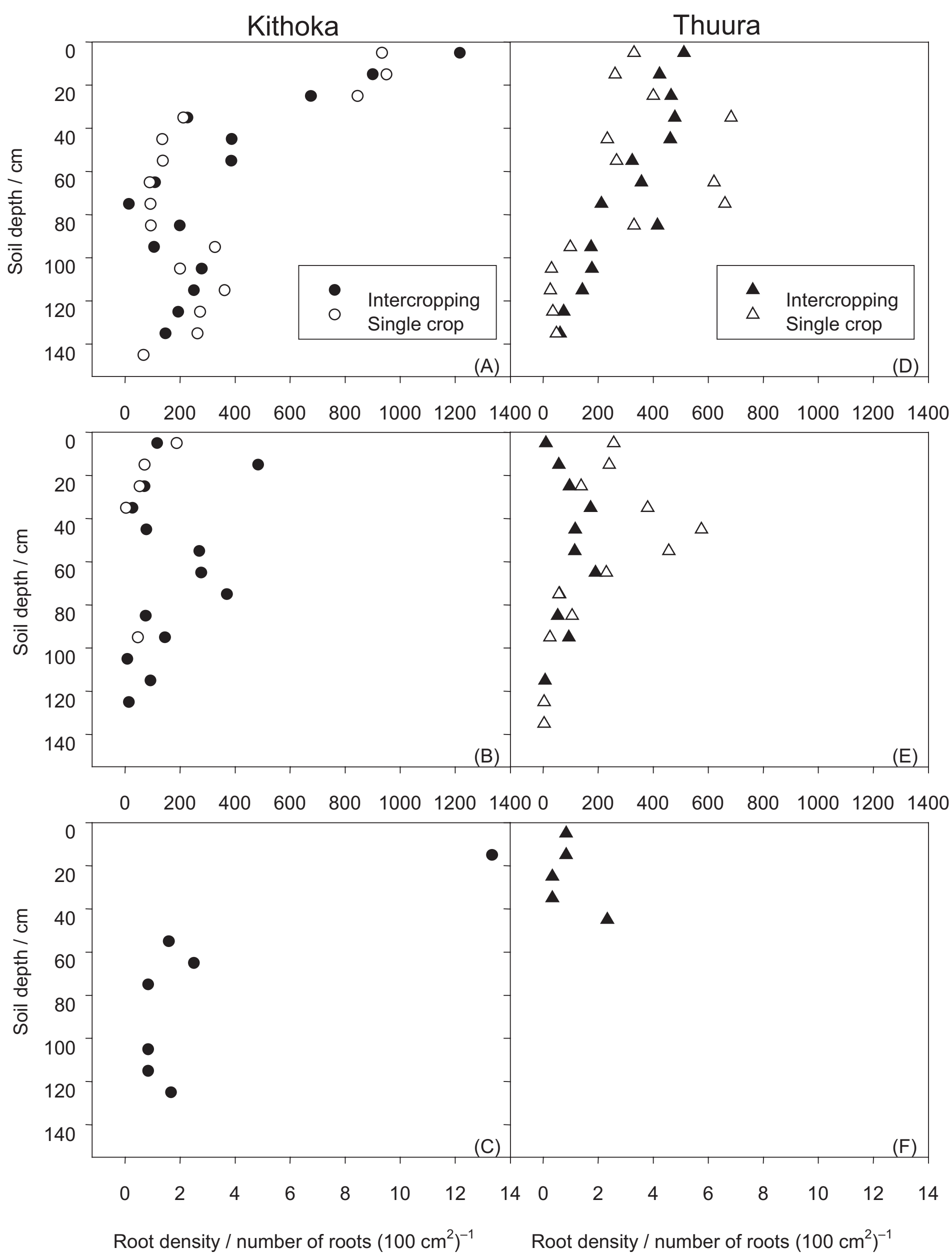

Figure 1: Vertical distribution of very fine (A, D), fine (B, E), and medium-sized roots (C, F) in the intercropping and single-crop fields of Kithoka (A–C) and Thuura (E–F). The vertical distributions of fine roots in the single-crop and intercropping systems of Kithoka differed significantly (Kolmogorov-Smirnov test; p = 0.004): on average, fine-root density was higher in the intercropping system than in the single-crop field (Wilcoxon Signed Rank Test, p = 0.002). No medium-sized roots were found in the soil of the single-crop fields.

3.2 Vertical root distribution

At both study sites and cropping systems, very fine roots (∅ < 0.5 mm) were even found in the largest soil depths investigated (down to ≈ 140 cm) (Fig. 1). In the intercropping system of Kithoka (Nitisol), fine roots (∅ 0.5 to 2 mm) occurred in greater soil depths (down to 130 cm) than in the single-crop field (maximum rooting depth, 100 cm), but the opposite result was found for the Thuura Gleysol (maximum rooting depth in the intercropping field, 120 cm; and in the single-crop culture, 140 cm). At both study sites, roots of medium size (∅ > 2 to 5 mm) were detected in the intercropping fields, but not in the single-crop systems. In the intercropping field of Kithoka, the medium-sized roots penetrated deeper into the soil (down to 130 cm) than in Thuura (down to only 50 cm).

In Kithoka, maximum values of fine root density (> 1400 very fine plus fine roots per 100 cm^2) were counted in 10–20 cm of soil depth in the intercropping system (Fig. 1). At that location, the vertical fine-root distribution along the soil profiles differed significantly between the cropping systems (Kolmogorov-Smirnov test; $p = 0.004$). On average along the vertical soil profile, the fine-root density was higher in the intercropping system than in the single-crop field (Wilcoxon Signed Rank Test, $p = 0.002$). No significant differences between the cropping systems were detected for the very fine roots. At the intercropping site of Thuura, the root densities along the vertical soil profile were not higher than in the single-crop system.

In Thuura as well as in Kithoka, the fine roots (∅ 0.5 to 2.0 mm) were more homogeneously distributed across the soil profiles of the intercropping fields than in the single-crop profiles; accordingly, the β values for the fine roots from the intercropping sites were higher (Fig. 2). The log β values, *i.e.,* the slopes of the log-transformed Eq. 1, were significantly different in a comparison of all four slopes (single-crop and intercropping fields of both localities; $F_{(3;37)} = 22.67$, $p < 0.001$) as well as in pairwise single-crop *vs.* intercropping comparisons ($F_{(1; \geq 16)} > 9.0$, $p < 0.01$). This finding is indicative of a larger fraction of fine roots in deeper soil layers of the intercropping systems in comparison with the single-crop fields. In accordance with these results, the solution of model (1) for the depth *d* revealed that in the intercropping fields, the uppermost 50% of the total fine roots counted in the entire soil profile were distributed over a thicker soil layer than in the single-crop fields (Fig. 2B): in the intercropping fields of both study sites, 50% of all fine roots were dispersed over the uppermost 36 cm of the soil, whereas in the single-crop systems, 50% of the fine roots were concentrated in the uppermost 15 cm (Kithoka) or 21 cm (Thuura), respectively.

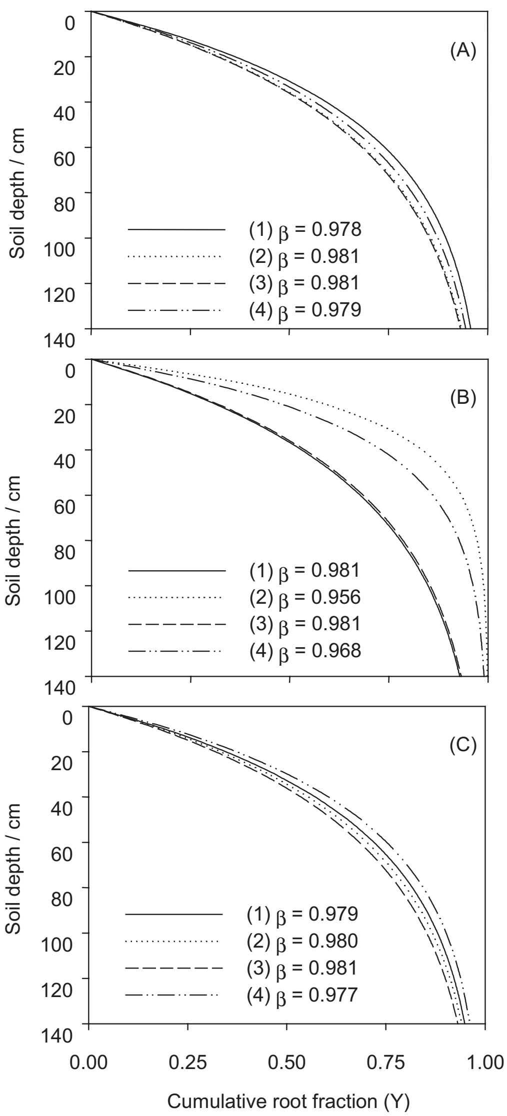

Figure 2: Regression curves of cumulative root distributions (*Y*) as a function of soil depth (*d*; cm) for very fine roots (A), fine roots (B), and the sum of very fine and fine roots (C) for the (1) Kithoka intercropping site, (2) Kithoka single-crop field, (3) Thuura intercropping site, and (4) Thuura single-crop field according to the function $Y = 1 - \beta^d$. Different lowercase letters indicate significant differences among the individual log β values of the cropping systems and localities ($p < 0.01$).

3.3 Particle-size analysis and soil-physical variables

At almost all soil depths of Thuura and Kithoka, the clay fraction was > 65% (Tab. 3). Thus, the texture of the soil was classified as pure clay according to *Ad-hoc Arbeitsgruppe Boden* (2005). The only exception was the horizon at 120–140 cm of soil depth in Thuura, where the clay fraction was only 63.8% and, therefore, the soil texture was categorized as loamy clay.

At each study site and at every depth of the soil, low soil bulk densities were observed (Tab. 4). However, high penetration resistance and low air permeability was measured at 40–60 cm of soil depth in both cropping systems of Kithoka, which was associated with a substantial increase in the fine-particle-size fractions (clay + fine silt) from 20–40 cm of depth to 40–60 cm of depth (Tab. 3). At all soil depths of Kithoka, higher air permeability was determined in the single-crop field than in the intercropping system. In Thuura, due to natural compaction, the penetration resistance slightly increased from the top- to the subsoil. At that location, lower penetration

Table 3: Clay content (%) at the intercropping sites of Thuura and Kithoka; and pH, concentrations of organic C and total N, C : N ratios, and effective cation-exchange capacity (ECEC) of all soil depths sampled at the single-crop sites of Kithoka and Thuura.

Kithoka (Haplic Nitisols [eutric])							**Thuura (Vitric Gleysols [eutric, epiclayic, endoclayic])**							
soil depth / cm	clay / %	pH	eCEC / $mmol_c\ kg_{DM}^{-1}$	C / %	N / %	C : N / g g^{-1}	soil depth / cm	clay / %	soil depth / cm	pH	eCEC / $mmol_c\ kg_{DM}^{-1}$	C / %	N / %	C : N
0–20	66.4	5.4	201	2.13	0.21	10	0–15	76.4	0–10	4.5	119	0.96	0.12	8
20–40	72.2	5.3	190	1.97	0.20	10	15–30	74.5	10–30	4.1	112	0.88	0.11	8
40–60	72.1	5.1	148	1.42	0.16	9	30–45	73.6	30–60	4.4	143	2.98	0.22	13
60–100	79.7	5.1	112	0.81	0.11	7	45–80	70.5	60–80	4.4	143	2.26	0.17	14
> 100	78.4	5.2	105	0.70	0.09	8	80–120	69.3	80–100	4.7	133	0.91	0.10	9
							120–140	63.8	> 100	4.6	141	0.54	0.07	8
							> 140	66.5						

resistance in the single-crop field in comparison to the intercropping system coincided with higher air permeability at each depth of soil sampling down to 100 cm.

3.4 Soil-chemical analyses

In Kithoka, the concentrations of C_{org} and the C : N ratios decreased continuously with soil depth, starting from 2.13% C and a C : N ratio of 10 in the topsoil down to 0.70% C and a C : N ratio of 8 below 1 m of depth (Tab. 3). The maximum concentration of N_t was determined at 40–60 cm of soil depth. In Thuura, peak concentrations of C_{org} and N_t as well as maximum C : N ratios were found at a depth of 30–80 cm. At Thuura, soil pH was lower than in Kithoka.

In Kithoka, ECEC decreased continuously from the topsoil to soil layers below 1 m of depth; whereas in Thuura, the ECEC exhibited a slight increase from the topsoil to the subsoil.

4 Discussion

4.1 Rooting depths in maize single-crop fields and in intercropping systems

On the contrary to our first hypothesis, the maximum rooting depth in the intercropping fields was not consistently larger than in the single-crop systems. The fact that no roots of medium size were present in the single-crop fields can be explained by the absence of the shrub crop *Cajanus cajan*, which develops coarser roots than *Zea mays* and *Phaseolus vulgaris*. The maximum rooting depth was below 1.4 m of soil depth. This result is in accordance with the global average of maximum rooting depths in cropland found by a meta-analysis ([2.1 ± 0.2] m), with the highest value detected in an individual study being 3.7 m in a field of *Medicago sativa* in Nebraska (*cf*. *Canadell* et al., 1996).

The ranges of pH and ECEC were typical for the soil types investigated and cannot be expected to impose restrictions to the root growth. The distinctly higher concentrations of exchangeable Mn in Thuura were the result of the redox gradient between groundwater and capillary fringe, which causes translocation and unequal distribution of Fe and Mn oxides and hydroxides.

In their vertical growth, the roots obviously experienced no restrictions exerted by the physical soil conditions. The maximum soil bulk density (1.1 g cm^{-3}) was distinctly below the minimum threshold of 1.4 g cm^{-3} that was considered critical for the root growth of an herbaceous crop on soils with large fractions of clay and silt and relatively low water contents (*Lipiec* et al., 2003). Air permeability was intermediate to very high in all investigated soil layers. At both study sites and in both cropping systems, the average penetration resistance of the soil was below the threshold of 2 MPa, which is considered critical for root growth in clayey soils of tropical sub-Saharan Africa (*Tekeste* et al., 2007). An exception was the layer at 40–60 cm of soil depth at the Kithoka site, where the average penetration resistance ranged between 3.0 and 3.5 MPa (Tab. 4). Nevertheless, roots found a way to reach deeper subsoil layers.

4.2 Vertical root distribution in maize single-crop fields and in intercropping systems

On the basis of a layer-wise comparison, the lack of consistent differences between the cropping systems leads us to reject our second hypothesis of a more intense coverage by fine or very fine roots in the intercropping fields. However, according to our third hypothesis, the higher β values of the distribution of fine roots (∅ 0.5 to 2.0 mm) in the intercropping fields are indicative of a more homogeneous vertical root distribution than in the single-crop systems. A relatively high fraction of fine roots, which have a high capacity of water uptake related to their biomass, in the subsoil might be more important for resource exploitation and for the uptake of water in particular than a high density of fine roots in individual soil horizons. Therefore, the β value that estimates the homogeneity of the vertical root distribution might be a more reliable measure of the plants' capability of resource acquisition than the pure number or biomass of roots in individual soil layers.

With its pronounced alternation of wet and dry seasons, the climate in the study region requires that the crops—and, in particular, their root systems—are adapted to desiccation of the soil. Maize is adapted to a wide variety of soils in the tropics. They range from sands to heavy clays, but maize is mostly grown on well-structured soils of intermediate texture (*Norman* et al., 1995). Common bean can be grown on soils varying from light sands to heavy clays, but preferably on fri-

Table 4: Soil bulk density (SBD), penetration resistance (PR), and air permeability (AP) at the single-crop and intercropping study sites in Kithoka and in Thuura (means of three replicate samples). Sampling depths were identical at the single-crop and the intercropping sites of a given locality.

Kithoka (Haplic Nitisols (eutric))							**Thuura (Vitric Gleysols (eutric, epiclayic, endoclayic))**							
single-crop				intercropping			single-crop				intercropping			
depth / cm	SBD / g cm^{-3}	PR / kPa	AP / μm^2	SBD / g cm^{-3}	PR / kPa	AP / μm^2	depth / cm	SBD / g cm^{-3}	PR / kPa	AP / μm^2	depth / cm	SBD / g cm^{-3}	PR / kPa	AP / μm^2
0–20	0.9	717	93	1.0	1018	24	0–15	1.0	1221	76	0–15	1.0	1362	37
20–40	1.0	882	110	1.0	1844	86	15–30	0.9	1345	40	15–30	1.1	1782	17
40–60	1.1	3445	55	1.1	3187	44	30–45	0.9	1094	72	30–45	0.9	1631	40
60–100	1.0	1298	116	1.0	1246	131	45–80	0.9	1159	195	45–80	1.1	1722	34
> 100	0.8	509		1.0	1891	127	80–100	1.1	1531	474	80–120	0.9	1240	59
							> 100	1.1	1859	64	120–140	1.0	1787	71

able soil. Although drought stress is common in major bean-producing areas, the crop is not particularly drought-tolerant (*Norman* et al., 1995). Therefore, where rains are erratic, the soil should be deep (*Kay*, 1979) and deeply rooted, as is the case in the area of our study. Nevertheless, during the dry season, the sites of both localities (Kithoka and Thuura) may be affected by drought. Therefore, most probably, the more homogeneous vertical distribution of fine roots across the soil is beneficial in periods with low amounts of precipitation, but high transpirational demand.

On a global scale, the average β values of terrestrial biomes range between 0.914 (tundra; indicative of 93% of the root biomass being concentrated in the uppermost 30 cm of the soil) and 0.976 (temperate coniferous forests; only 52% of the root biomass in the uppermost 30 cm) (*Jackson* et al., 1996); however, β values higher than 0.98 have been found in individual studies on temperate deciduous forest trees (*Gale* and *Grigal*, 1987; *Thomas*, 2000). According to the metastudy by *Jackson* et al. (1996), croplands exhibit a global average β value of 0.961 (70% of the root biomass concentrated in the uppermost 30 cm). Hence, in a global comparison, the high β values (0.956–0.981) determined in our study for the fine and the very fine roots are indicative of a relatively uniform vertical root distribution throughout the investigated rooting depth of up to 1.4 m, and of a fraction of only ≈ 50% of the roots concentrated in the uppermost 30–40 cm of the soil of the intercropping fields.

4.3 Consequences of the root distribution for resource acquisition by crops

Maize and legume roots compete for water and nutrients. This competition, however, is not as strong as the intraspecific competition because cereal and legume roots have a different growing pattern: cereal roots have their maximum development near the soil surface, while legume roots also tend to develop intensively in deeper soil layers (*Benzing*, 1995). Likewise, shrubs, among which the pigeon pea is counted, exhibit higher maximum rooting depths than crops (*Canadell* et al., 1996). With regard to our study sites, we hypothesize that the more homogeneous vertical distribution of fine roots results in a more efficient resource acquisition at the intercropping fields in comparison to the single-crop fields, where the strong intraspecific competition between the maize roots prevails. In a study conducted in the subtropical part of Japan, maize was found to be capable of very efficiently depleting the water resources of confined regions of the soil, thereby creating distinct nonequilibria of water flow between the soil layers. Therefore, to cope with shortage of water supply, the depth of the most densely rooted soil layer was more important to the water supply of this species than the maximum rooting depth (*Yu* et al., 2007). Most probably, the capability of maize to efficiently deplete the water resources of the soil is related to the generally higher root length per unit soil volume of monocotyledonous crops compared to dicotyledonous ones (*Meyer* and *Barrs,* 1991). This kind of spatial complementarity among crop species in the use of resources also pertains to nutrients: in a study conducted in Sumatra, the woody intercrop *Peltophorum dasyrrachis* was shown to take up relatively more N from deeper soil layers compared to maize, due to a greater proportion of *Peltophorum* roots in deeper soil horizons (*Rowe* et al., 2001). In addition, *Peltophorum* roots arrived earlier in these layers than maize roots (*Rowe* et al., 2001). It is possible that in the intercropping systems of our study sites, such a temporal complementarity might play an important role as well: The pigeon pea might utilize stored soil water after the rains have ceased and the short-season crops such as maize and beans have been harvested (*Dart* and *Krantz*, 1977).

5 Conclusion

The high β values (0.956–0.981) determined for the fine and the very fine roots are indicative of a relatively uniform vertical root distribution throughout the investigated rooting depth of up to 1.4 m, and of a fraction of only ≈ 50% of the roots concentrated in the uppermost 30–40 cm of the soil of the intercropping fields. Taking into consideration the morphological traits and the developmental patterns of those crops, these findings let us conclude that intercropping is connected to a spatial as well as a temporal complementarity among species in the use of essential resources, *i.e.,* water and nutrients, from the soil. This should result in a more complete use of those soil resources at the intercropping sites than at the ones with single-crop systems. Hence, intercropping, which is the traditional way of land management in the study area, might be more sustainable and better adapted to local ecological conditions than single-crop systems.

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