

VARIABILITY IN THE ROOT SYSTEM OF EAST AFRICAN BANANA GENOTYPES

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ABSTRACT

The banana (*Musa* spp.) root system is important for plant anchorage and the uptake of nutrients and water and thus, strongly influences plant growth and subsequent yields. Previous research studies on the *Musa* spp. root system have predominantly focused on high value export dessert bananas (AAA group) and plantains (AAB group). The study reported in this paper compared root system development of East African highland bananas (AAA-EA group) with other *Musa* groups. Two separate studies were conducted. One of the studies focused on variability in root system development of 25 *Musa* genotypes, including 10 East African highland bananas, while the other experiment assessed variability in root distribution for 'Kibuzi' (AAA-EA, cooking banana), 'Gonja' (AAB, plantain) and 'Sukali Ndiizi' (AAB, dessert banana). Plants in the first study were completely excavated at 20 weeks after planting (WAP), while a sub-set of 5 East African highland bananas was also assessed at flower emergence. A 90° section of the root system was assessed for pre-flowering plants in the second trial. Significant positive correlations were found between shoot and root traits for the plants assessed at 20 WAP and at flower emergence. In addition, there was no significant genotypic effect on the shoot root ratio indicating that all genotypes had a similar partitioning of dry matter between the shoot and the root system. In contrast, at 20 WAP significant genotypic effects were observed on individual shoot and root traits. Soil depth and genotype significantly ($P < 0.001$) affected root dry weight and cord root length of the pre-flowering plants. The largest root system was observed for the AAA-EA 'Kibuzi', which also exhibited the most vigorous shoot and sucker (i.e., lateral shoot) growth again suggesting a strong shoot root relationship. Most roots were found in the upper 45 cm soil layer for all 3 genotypes. Horizontal distance from the plant x genotype had no significant effect on the root traits, indicating that all 3 genotypes had an evenly distributed root system up to 90 cm from the plant base.

Key Words: Dry matter partitioning, genotypes, *Musa* spp., root distribution

RÉSUMÉ

Le système des racines de banane (*Musa* spp) est important pour l'anchorage de plante et saisir vite les substances et l'eau et ainsi, les fortes influences de croissance de plante et les productions subséquentes. Les études de recherche antérieures sur le système des racines *Musa* spp. ont prédominamment focalisé sur l'export des bananes de dessert de haute valeur (groupe AAA) et plantains (groupe AAB). L'étude rapportée dans cet article a comparé le développement du système des racines des bananes de région de montagne de l'Afrique de l'est (groupe AAA-EA) avec les autres groupes *Musa*. Deux études séparées étaient conduites. Une des études a focalisé sur la variabilité dans le développement de systèmes des racines de 25 génotypes *Musa*, incluant 10 bananes de région de montagne de l'Afrique de l'est pendant que les autres expériences évaluées la variabilité dans la distribution des racines pour 'Kibuzi' (banane de cuisson, AAA-EA), 'Gonja' (plantain, AAB) et 'Sukali Ndizi' (banane de dessert, AAB). Les plantes dans la première étude étaient complètement excavées à 20 semaines après plantation (WAP), pendant qu'un sous groupe de 5 bananes de région de montagne de l'Afrique de l'est était aussi évalué à l'émergence de la fleur. En plus. Il n'y avait pas d'effet génotypique significatif sur la proportion de racines de

pousse indiquant que tous les génotypes avaient une partition similaire de matière sèche entre la pousse et le système de racines. Par contraste, à 20 WAP les effets génotypes significatifs étaient observés sur la pousse individuelle et les traits de racine. La profondeur du sol et le génotype ont significativement ($P < 0,0001$) affecté le poids de racine sèche et la longueur de cordon de racine des plantes pré fleurit. Le plus large système de racines était observé pour le AAA-EA 'Kibuzi', lequel a aussi exhibé la plus vigoureuse pousse et ventouse (c-a-d pousse latérale) de croissance suggérant encore une forte relation de racine de pousse. La majorité des racines était trouvée dans la couche supérieure de sol de 45 cm pour tous les trois génotypes. La distance horizontale de génotype x de plante n'avait pas d'effet significatif sur les traits de racine, indiquant que tous les trois génotypes avaient un système de racines uniformément distribué jusqu'à 90 cm à partir de la plante de base.

Mots Clés: partition de matière sèche, génotypes, *Musa* spp., distribution des racines

INTRODUCTION

Bananas and plantains (*Musa* spp.) provide a staple food crop for millions of people in the tropics. Productivity is however, constrained by poor agronomic practices, pests and diseases, drought stress and declining soil fertility (Rubaihayo *et al.*, 1994; Gold *et al.*, 1999). These constraints directly or indirectly influence the root growth and physiological functioning. Poor root systems may not be able to supply the plant with the necessary nutrients and may be more susceptible to nematodes. Bananuka (2001) attributed drought susceptibility of 'Entaragaza' (AAA-EA, cooking banana) partly to its poorly ramified root system compared to that of 'Sukali Ndiizi' (AAB, dessert banana). Thus, improving the root systems may help in overcoming production such as drought stress.

Genetic improvement however, requires in-depth knowledge of the variability in root parameters and their genetic control (O'toole and Bland, 1987). Atkison (1989) reviewed prospects for improving resource acquisition by the plant root system and reported that variability in morphological characteristics had a greater potential for exploitation than physiological characteristics such as uptake rates. Variability in root development amongst *Musa* spp. genotypes has been reported (Swennen *et al.*, 1986). In hydroponics Swennen *et al.* (1986) reported differences in root branching patterns between plantains and bananas. For plants of the same height 'Agbagba' (AAB, plantain) formed fewer roots than 'Robusta' (AAA, dessert banana). In a related study, also conducted under hydroponic conditions, Bananuka (2001) reported cultivar differences in cord root characteristics. 'Gonja' (AAB, plantain) and 'FHIA 23' had the highest

root growth rates while the highland bananas 'Entaragaza' and 'Kibuzi' had the lowest root growth rates. Blomme *et al.* (2000) assessed the root system of a wide range of *Musa* spp. genotypes grown under field conditions and reported a genotype effect on most root traits. This study was conducted in Nigeria, at sea level and did not include East African highland bananas. The main objective of the present study was to determine variability in root system size and distribution amongst *Musa* genotypes with a special focus on the East African highland bananas.

MATERIALS AND METHODS

Variability in root system development among *Musa* spp. genotypes. This experiment was conducted at the Kawanda Agricultural Research Institute (KARI) located 32°32'E and 0.25°N at an elevation of 1,177 m above sea level. The climate is moist, sub humid, with a mean annual rainfall of 1,132 mm which is bimodally distributed. The main wet season begins in April while the short rains begin in September. The soils are classified as Eutric Ferralsols according to USDA (Yost and Estwaraan, 1990). They are reddish-brown loams, 25 cm deep, overlying uniform red clay. Soil samples, taken during the establishment of the trial, were analyzed for soil texture, N, P, K, Mg, Na, Ca, organic matter and soil pH (Table 1).

The experiment was established in early April 2001. Sword suckers obtained from true to type plants were prepared and planted as recommended by Swennen (1990). The planting hole size was 60 x 60 x 60 cm. At planting, 10 kg of farm yard manure per plant was mixed in the top soil in order to increase soil fertility. In addition, in order to control nematodes and weevils, 20 g of Furadan

was applied per plant at planting. A total of 25 genotypes were assessed at 20 weeks after planting (20 WAP), while a subset of 5 East African highland bananas was assessed at flower emergence of the plant crop. The experimental layout was a randomized complete block design with two replications of two plants per genotype. The plant spacing was 3x3 m for plants assessed at 20 WAP, while a 4x4 m spacing was applied for plants assessed at flower emergence of the plant crop. The plants were grown under monoculture and no mulch was applied. Weeds were controlled by spraying the herbicide Agrosate at monthly intervals. All suckers (i.e., lateral shoots) were allowed to develop.

Quantitative shoot and root traits were assessed. The shoot traits included: height of the plant (PH, cm), circumference of the pseudostem at soil level (PC, cm), number of leaves (NL) and leaf area (LA, m²). Plant height was measured from soil level to the point where the two highest petioles meet. Leaf length and leaf widest width were measured and LA was determined according to Obiefuna and Ndubizu (1979). In addition height of the tallest sucker (HS, cm), leaf dry weight (LW, g), pseudostem dry weight (PW, g) and corm dry weight (CW, g) were measured. In order to assess below ground traits, the mats were completely excavated. Root characteristics included the number of cord roots (NR), root dry weight (RW, g) and the average basal cord root diameter (AD, cm) measured with a Vernier calliper. The cord root length (LR, m) was measured using the line intersect method (Tennant,

1975). Roots were randomly spread on a 3 cm grid and all intersection points of the cord roots with the grid lines were counted. Root length was then estimated as follows: Root length = Number of intercepts x 2.3571 (length conversion factor for a 3 cm grid). Dry weight of plant tissue was obtained by drying the samples in an oven at 70°C for one week.

Data analysis was carried out using the Genstat (1996) statistical package. Total phenotypic variance was partitioned according to sources of variation of genotype and replication. Correlations between shoot and root traits were assessed using Pearson's rank correlation coefficient in Minitab (1998).

Variability in root system distribution among three Musa genotypes. This experiment was carried out at the Makerere Agricultural Research Institute Kabanyolo (MUARIK) located at 0°28'N, 32°37'E and 1,150 m above sea level. The area has a mean annual rainfall of 1,300 mm which is bimodally distributed. The soils are classified as Eutric Ferralsols according to USDA (Yost and Estwara, 1990). The soil chemical and physical characteristics are presented in Table 1.

The trial was established in April 1999, while pre-flowering plants of the second ratoon crop were assessed in August 2001. Three tons of farm yard manure was annually applied per hectare. The genotypes assessed were 'Sukali Ndiizi' (AAB, dessert banana), 'Kibuzi' (AAA-EA, cooking banana) and 'Gonja' (AAB, plantain). The field layout was a completely randomized

TABLE 1. Soil physical and chemical characteristics for experiment 1 and 2

Experiment	Soil depth (cm)	pH	OM		N	P	K	Na	Textural class
			%						
						ppm	Mg/100g soil		
1	0-20	4.75	3.45	0.1	4.88	10.52	0.46	Sandy clay loam	
	20-40	4.8	2.8	0.12	2.15	6.44	1.15	Sandy clay loam	
2	0-15	5.3	3.85	0.18	44.9	1	0.11	Sandy clay loam	
	15-30	5.3	2.74	0.13	39.05	1.01	0.12	Sandy clay loam	
	30-45	5.2	1.41	0.09	4.99	0.85	0.09	-	
	45-60	5.2	1.19	0.1	4.33	0.51	0.05	-	
	60-75	5.5	1.17	0.09	7.31	0.41	0.04	-	
	75-90	5.6	0.83	0.08	5.02	0.63	0.06	-	
	90-105	5.6	0.64	0.06	3.27	1.05	0.12	-	
	105-120	5.6	0.8	0.06	2.76	0.53	0.05	-	
Critical levels*		>5.2	>3.0	>0.2	>15	>0.44	<1.0		

OM: Organic matter

*: Critical levels as quoted by Odeke *et al.* (1999)

design. Plant spacing was 3x3 m in order to avoid overlapping of roots from adjacent plants. Eight mats per genotype were assessed.

A 90° section, at the side of the tallest sucker and to the right of a straight line drawn through the mother plant and the tallest sucker, was excavated for each plant (Fig. 1). Roots were taken from soil blocks at distances of 0-30, 30-60 and 60-90 cm from the corm. For each horizontal distance, 8 soil blocks, 15 cm high, were taken from the surface up to a depth of 120 cm. For each soil block, the roots were rinsed free of soil. The cord root length was determined according to Tennant (1975). Root samples were subsequently oven dried and root dry weight was measured.

The data was log₁₀ (X+0.5) transformed and subjected to analysis of variance (ANOVA) test using the Genstat statistical package.

RESULTS AND DISCUSSION

Variability in root system development among *Musa* spp. genotypes. At 20 WAP the different AAA-EA genotypes exhibited significant (P<0.05) effect on all shoot and root traits (Table 2). The East African highland bananas ‘Kisansa’, ‘Nakinyika’ and ‘Butobe’ had high numbers of cord roots comparable to the best performers *Musa acuminata burmannicoides*, ‘Yangambi km5’ and ‘Obino’ Ewai’. Except for *M. balbisiana* and ‘FHIA 17’, the highland banana genotypes ‘Namadhi,’ ‘Katalibwambuzi’, ‘Imbululu’ and ‘Musakala’ had the lowest number of cord roots.

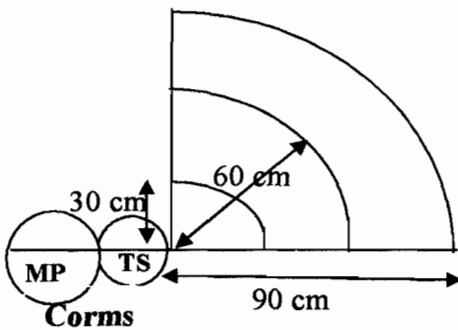


Figure 1. Schematic representation of area excavated: MP: Mother plant and TS: tallest sucker.

TABLE 2. Mean square values and significance for plant growth traits of plants assessed at 20 weeks after planting (20 WAP) and at flower emergence of the plant crop (FL)

Age	Source of variation	df	Growth traits #										
			LA	LW	PH	PC	PW	CW	NR	LR	AD	RW	S/R
20 WAP	Replication	1	5.69	3.3	3728.3	569.3	116.35	6.46	8501	0	0.02	0.33	229.12
	Genotype	24	2.56***	1.68***	1104.3***	153.3***	21.7***	3.91***	9687***	8.28**	0.02***	0.66***	15.18
	Residual	74	0.58	0.33	284.5	37.	6.2	1.29	3655	3.97	0.01	0.26	13.53
FL	Replication	1	1.79	1.6	238	20.4	5.28	2.69	4004	1.58	0.01	3.16	4.48
	Genotype	4	1.8*	4.8*	1330.3	48.27	1.36	9.33	100712**	4.71	0.003	1.81*	37.55
	Residual	14	4.3	1.44	848.1	65.02	6.19	3.59	14796	2.16	0.012	4.6	21.15

#: LA: Leaf area (m²), LW: Leaf dry weight (g), PH: Plant height (cm), PC: Pseudostem circumference (cm), PW: Pseudostem dry weight (g), CW: Corm dry weight (g), NR: Number of cord roots, LR: Cord root length (m), AD: Average basal cord root diameter (cm), RW: Root dry weight and S/R: Shoot root ratio
*, ** and *** significant at 5, 1 and 0.1%, respectively

At flower emergence of the plant crop, mats of 'Namadhi' had a cord root number that was significantly higher than the number of cord roots of 'Imbululu', 'Mbwazirume' and 'Musakala' (Table 3). This could be attributed to its non-regulated suckering behaviour and hence to a large number of vigorous suckers which produce a large number of roots. These results are in agreement with findings of Blomme *et al.* (2000) for plants assessed in the field and with Swennen *et al.* (1986) for plants assessed under hydroponic conditions.

Primary cord roots play a major architectural role in distributing lateral roots in the soil. This may imply that genotypes with a higher number of cord roots have a potential to increase their root length and thus, surface area for absorption. *Musa acuminata burmannicoides*, 'Yangambi km5', 'Nakinyika', 'Kisansa' and 'FHIA 3' had the highest values for cord root length (Table 4). Apart from 'FHIA 3', the tetraploid hybrids had cord root lengths which were not significantly different from other genotypes. There were no significant differences in cord root length for highland banana mats assessed at flower emergence of the plant crop (Table 3).

Generally, basal cord root diameter increased with an increase in ploidy level. This is in agreement with results of Blomme *et al.* (2000) and Monnet and Charpentier (1965). However, the diploid *Musa balbisiana* plants had some of

the thickest roots and were thus, an exception to the rule. Large root diameters are important in enhancing lodging resistance and penetration capacity (O'toole and Bland, 1987). As expected, within the triploid highland banana genotypes there were no significant differences in average basal cord root diameter.

Significant ($P < 0.05$) cultivar differences for root dry weight were evident within the highland bananas at 20 WAP. 'Kisansa', 'Nakinyika' and 'Enyeru' had the highest root dry weights (Table 4) amongst the east African highland bananas. The lowest root dry weights were recorded among the diploids with *Musa acuminata microcarpa* performing poorest. For highland banana mats assessed at flower emergence of the plant crop, root dry weight for 'Namadhi' was significantly ($P < 0.05$) higher than that of 'Imbululu', 'Mbwazirume' and 'Enyeru'.

Significant positive correlations were observed between shoot and root growth traits (Table 5). This is in agreement with earlier reports by Blomme (2000) and Blomme and Ortiz (1996a, b). In addition, genotype did not have a significant effect on the shoot root ratio for mats assessed at 20 WAP and at flower emergence of the mother plant (Table 2). Thus plant dry matter partitioning is similar across cultivars within the AAA-EA confirming observations made by Blomme (2000). Hence alternating the shoot root ratio through a breeding program may be difficult.

TABLE 3. Genotype, plant growth traits and shoot root ratio for highland banana mats assessed at flower emergence of the plant crop (Means and LSD values)

Genotype	Growth traits#						
	LA	CW	NR	LR	AD	RW	S/R
Imbululu	16.31	1612	555	328.1	0.608	5.35	17.3
Namadhi	33.75	2816	984	586.9	0.588	10.9	14
Mbwazirume	19.94	1886	694	350.6	0.606	7.63	14.6
Enyeru	26.89	2583	824	333	0.604	6.7	21
Musakala	23.29	2183	780	407.5	0.541	9.01	13.7
LSD (5%)	9.95	ns	185.6	ns	ns	3.25	ns

#: LA: Leaf area (m^2), LW: Leaf dry weight (g), PH: Plant height (cm), PC: Pseudostem circumference (cm), PW: Pseudostem dry weight (g), CW: Corm dry weight (g), NR: Number of cord roots, LR: Cord root length (m), AD: Average basal cord root diameter (cm), RW: Root dry weight and S/R: Shoot root ratio

*, ** and *** significant at 5, 1 and 0.1%, respectively
ns: Not significant

Variability in root system distribution among three *Musa* genotypes. Nutrient levels declined with an increase in soil depth (Table 1). The pH, levels of potassium, phosphorus and micro nutrients were within the critical requirements. Nitrogen levels were however low.

Genotype, soil depth and genotype x soil depth had a significant ($P < 0.05$) effect on both root dry weight and cord root length (Table 6). However, horizontal distance from the plant x genotype had no significant effect on the root traits, indicating that all 3 genotypes had an evenly distributed root system up to 90 cm from the plant base.

Root dry weight decreased sharply down the soil profile for all three cultivars (Fig. 2A). Most roots were found in the upper 45 cm soil layer. 'Sukali Ndiizi' had a significantly ($P < 0.05$) higher

root dry weight in the top 15 cm soil compared to 'Kibuzi' and 'Gonja'. For the rest of the profile 'Sukali Ndiizi' and 'Gonja' had no significant differences in root dry weight or cord root length (Fig. 2). In the 15-45 cm soil depth 'Kibuzi', had a relatively higher root dry weight than 'Sukali Ndiizi' and 'Gonja'. The largest root system was observed for the AAA-EA 'Kibuzi', which also exhibited the most vigorous shoot and sucker growth again suggesting a strong shoot root relationship. A deep root system makes a plant more drought resistant (Araya *et al.*, 1998; Bananuka, 2001) as water can be absorbed from deeper soil layers. An increase in the soil volume explored enables a plant to better utilize the available soil resources. In our study we did not observe major differences amongst the genotypes

TABLE 4. Genotype, genome, plant growth traits and the shoot root ratio for plants assessed at 20 weeks after planting (Means and LSD values)

Genotype	Genome	Growth traits#						
		LA	CW	NR	LR	AD	RW	S/R
Wild diploids								
<i>Musa acuminata burmanica</i> (Calcutta 4)	AA	2.22	120	116.8	33	0.48	0.63	12.63
<i>Musa acuminata malaccensis</i> (Pahang)	AA	2.51	381	148.8	49.9	0.56	0.99	7.43
<i>Musa acuminata microcarpa</i> (Pisang J. Buaya)	AA	1.03	209	134.8	24.1	0.47	0.43	9.59
<i>Musa acuminata burmannicoides</i>	AA	4.2	228	259.3	69.7	0.48	1.5	9.54
<i>Musa acuminata truncata</i>	AA	2.17	261	135	42	0.59	0.83	7.25
<i>Musa balbisiana</i>	BB	1.17	305	76.5	25.5	0.66	0.5	9.11
East African Highland bananas								
Imbululu	AAA-EA	1.11	175	105	27.1	0.54	0.53	7.41
Butobe	AAA-EA	1.7	312	186.8	41.2	0.58	0.91	7.02
Mbwazirume	AAA-EA	1.61	149	136	35.7	0.58	0.8	7.82
Nakitembe omuganda	AAA-EA	1.63	196	153.3	38.7	0.53	0.93	6.01
Enyeru	AAA-EA	1.72	241	171.8	55.6	0.58	1.13	6.01
Nakinyika	AAA-EA	2.2	204	197.3	66.9	0.55	1.38	6.68
Musakala	AAA-EA	1.82	533	113.3	36.2	0.57	0.74	7.73
Kisansa	AAA-EA	3.04	107	199	66.8	0.6	1.56	8.19
Namadhi	AAA-EA	190.6	2.2	103.3	43.6	0.53	0.83	12.35
Katalibwambuzi	AAA-EA	1.64	85	103.3	25.2	0.52	0.5	12.3
Introduced genotypes								
Gros michel	AAA	2.94	83	165	45.5	0.6	1.14	8.91
Cavendish	AAA	2.77	200	158.8	56.8	0.57	1.4	9.21
Yangambi km 5	AAA	3.19	224	243.3	67.2	0.62	1.89	6.15
Obino l'Ewai	AAB	2.49	332	204.3	51.5	0.56	1.18	7.62
Pisang Awak	ABB	1.87	157	217.8	57.4	0.57	1.16	7.62
FHIA 17	AAAA	2.3	161	97.8	39.5	0.67	1.03	7.03
FHIA 3	ABB x AA	3.96	153	229.3	65.9	0.76	1.88	11.34
TMPx 5511-2	AAB x AA	2.65	148	169.3	54.3	0.66	1.25	7.45
TMPx 548-9	AAB x AA	2.02	204	127	40.1	0.64	0.83	8.82
LSD (5%)		1.07	163.1	85.18	28.06	0.096	0.72	ns**

#: LA: Leaf area (m^2), LW: Leaf dry weight (g), PH: Plant height (cm), PC: Pseudostem circumference (cm), PW: Pseudostem dry weight (g), CW: Corm dry weight (g), NR: Number of cord roots, LR: Cord root length (m), AD: Average basal cord root diameter (cm), RW: Root dry weight and S/R: Shoot root ratio
*, ** and *** significant at 5, 1 and 0.1%, respectively
ns: Not significant.

in root distribution and thus, soil volume explored. Hence, the drought resistance of ‘Sukali Ndiizi’ described by Bananuka (2001) may not be linked to root distribution.

CONCLUSIONS

The results indicate a wide variability in root system size amongst the *Musa* genotypes. At 20 weeks after planting, some of the East African highland bananas were amongst the genotypes with the largest root system size. Significant positive correlations between shoot and root traits of the mats were observed during the vegetative

and reproductive phase. In addition, the effect of genotype on the shoot root ratio was not significant, indicating that all genotypes had a similar partitioning of dry matter between the shoot and the root system. Soil depth and genotype significantly ($P < 0.001$) affected root dry weight and cord root length of the pre-flowering plants, while horizontal distance from the plant had no significant effects on the root traits. Due to the similar shoot root ratio observed across genotypes in this study, future research aimed at improvement of the root system should preferably focus on physiological aspects of root function such as uptake efficiency of water and mineral nutrients.

TABLE 5. Correlation coefficients and significance level for correlations between shoot and root traits for mats assessed at 20 weeks after planting (above the diagonal) and at flower emergence of the plant crop (below the diagonal)

Traits	Traits#							
	LA	LW	PW	CW	RW	LR	NR	AD
LA		0.93***	0.87***	0.87***	0.84***	0.78***	0.70***	0.27
LW	0.79		0.94***	0.91***	0.84***	0.76***	0.67***	0.42*
PW	0.87***	0.84***		0.93***	0.89***	0.83***	0.74***	0.43*
CW	0.86***	0.68**	0.87***		0.87***	0.78***	0.66***	0.48*
RW	0.51*	0.56*	0.60**	0.57**		0.94***	0.84***	0.41*
LR	0.42	0.41	0.36	0.42	0.65**		0.86***	0.24
NR	0.69***	0.68***	0.63**	0.73***	0.68***	0.6**		0.07
AD	-0.38	-0.15	-0.37	-0.26	-0.32	0.2	-0.2	

#: LA: Leaf area (m²), LW: Leaf dry weight (g), PH: Plant height (cm), PC: Pseudostem circumference (cm), PW: Pseudostem dry weight (g), CW: Corm dry weight (g), NR: Number of cord roots, LR: Cord root length (m), AD: Average basal cord root diameter (cm), RW: Root dry weight and S/R: Shoot root ratio
 *, ** and *** significant at 5, 1 and 0.1%, respectively

TABLE 6. Mean square values and significance for root dry weight and cord root length for plants assessed in experiment 2

Source of variation	d.f	Root dry weight	Cord root length
Genotype	2	0.67***	7.68***
Horizontal distance	2	0.55***	0.60
Soil depth	7	42.53***	121.66***
Genotype x horizontal distance	4	0.07	0.67
Genotype x soil depth	14	0.13***	0.87***
Horizontal distance x soil depth	14	0.26***	0.55*
Replication	7	0.36	0.92
Residual	196	0.05	0.31

*, ** and *** significant at 5, 1 and 0.1%, respectively

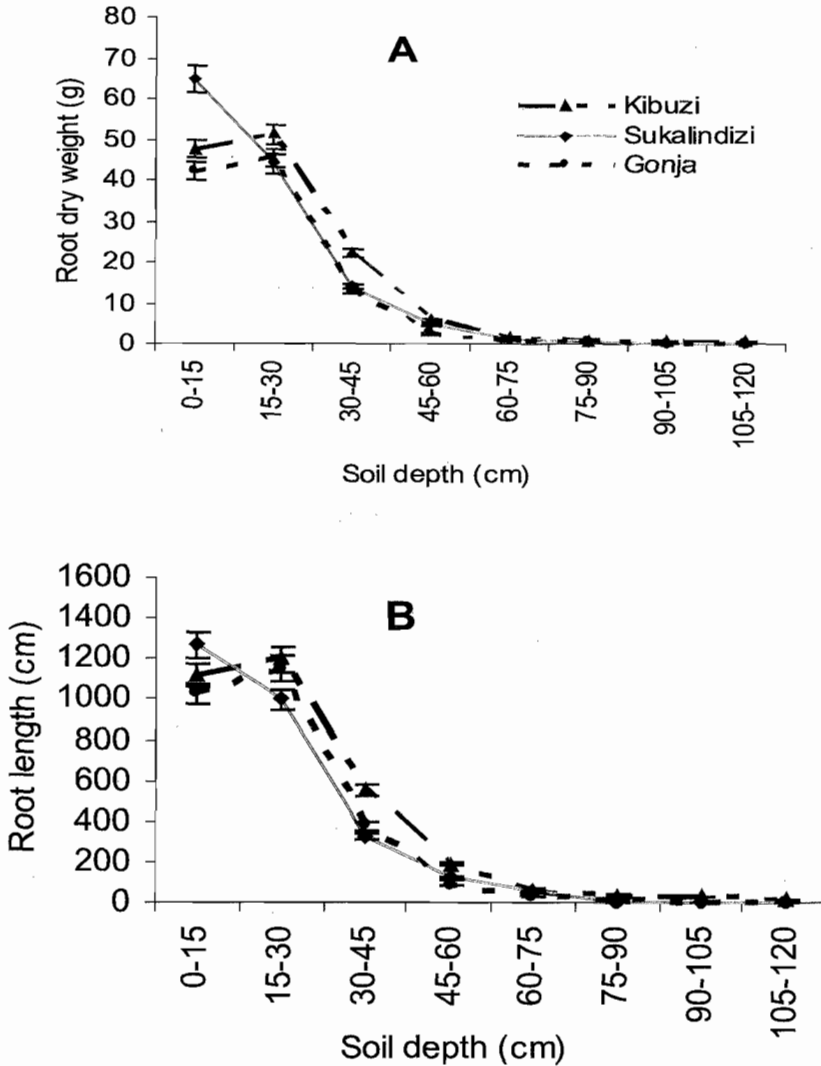


Figure 2. Variability in distribution for root dry weight (A) and cord root length (B) according to soil depth.

In addition, research on tensile or pulling strength of the roots could inform breeders about genotypes which may be less prone to toppling.

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