Methodologies for root system assessment in bananas and plantains (*Musa* spp.)

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Abstract

The root system of field-grown plantain and banana (*Musa* spp.) plants has been little investigated because whole plant excavation is tedious and time consuming. Four methods for measuring root system size were assessed. A first approach, early screening, determines the entire root system of nursery-grown juvenile plants to forecast root growth in the field of adult plants. Few significant root trait correlations were observed between juvenile and adult plants. Hence root characteristics of adult plants cannot be adequately estimated from the root size of young plants. A second approach was based on regression of root traits on shoot traits. Regression equations attributed at least 90% of the variation in root growth to variation in shoot development, but models were not universal. Indeed shoot-root ratios vary according to the plant developmental stage and environmental conditions and thus need to be assessed at each location. A third method relied on soil core sampling. Root measurements in two soil core samples could estimate the size of the entire root system with at least 80% accuracy. This method is attractive because it only requires 5% of the time needed to excavate the whole root system. In addition, models to estimate root traits of the mat (mother with daughter plants) were significant irrespective of the suckering behaviour of the variety. The fourth approach consisted in assessing electrical capacitance to quantify root biomass as done in other plant species. *Musa* plant tissue contains a lot of water and thus secures a high electrical conductivity. Very few significant correlations between capacitance values and root system traits were found. In conclusion, root system assessment based on root core sampling is proposed as it estimates well the size of the entire root system in a fast, cheap and non-destructive way.

Resumen - Metodologías para evaluar el sistema radical en bananos y plátanos

La investigación enfocada al sistema radical de plantas de banano y plátano (*Musa* spp.) desarrolladas en el campo ha sido muy poca, debido a que excavar plantas completas es tedioso y lento. Se evaluaron cuatro métodos para medir el tamaño del sistema radical. El primer método, que es el de evaluación temprana, determina todo el sistema radical de las plantas juveniles desarrolladas en el invernadero para pronosticar el crecimiento de la raíz de plantas adultas en el campo. Se observaron únicamente unas pocas correlaciones significativas para las características de la raíz entre plantas juveniles y adultas. Por lo tanto, las características de la raíz de plantas adultas no pueden ser estimadas adecuadamente por el tamaño de la raíz de las plantas jóvenes. El segundo método se basó en la regresión de las características de la raíz sobre las características de los hijos. Las ecuaciones de regresión atribuyeron al menos un 90% de la variación en crecimiento de la raíz a la variación en el desarrollo del hijo; sin embargo, los modelos no fueron universales. En efecto, los cocientes hijo-

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raíz varían de acuerdo con la etapa de desarrollo de la planta y con las condiciones ambientales, por lo que deberán ser evaluadas en cada sitio. El tercer método se basó en el muestreo de suelo con barreno. Las mediciones de raíz en dos muestras de suelo con barreno podrían estimar el tamaño completo del sistema radical con al menos un 80% de exactitud. Este método resulta atractivo ya que se tarda únicamente un 5% del tiempo que llevaría excavar el sistema radical completo. Además, los modelos para estimar las características de la raíz de la unidad de producción (madre con plantas hijas) fueron significativos, sin importar el comportamiento de los hijos de la variedad. El cuarto método consistió en evaluar la capacitancia eléctrica para cuantificar la biomasa de la raíz, como se realiza en otras especies de plantas. El tejido de las plantas de *Musa* contiene mucha agua, lo que asegura una alta conductividad eléctrica. Se encontraron muy pocas correlaciones significativas entre los valores de capacitancia y las características del sistema radical. En conclusión, se propone utilizar el método de muestreo de raíz con barreno, ya que éste ofrece una buena estimación del tamaño total del sistema radical, de una manera rápida, barata, y sin destrucción.

Introduction

Roots constitute the link between the plant and the soil thereby providing anchorage and guaranteeing nutrient and water uptake. Roots of plantain and banana (*Musa* spp.) are also sources of plant growth regulators that contribute to lateral shoot (known as suckers) development and thus perennial growth (De Langhe *et al.* 1983, Martin Prével 1987, Stover and Simmonds 1987, Lahav and Turner 1989, Price 1995).

Research on *Musa* root systems is remarkably limited despite the paramount problems with nematodes and longevity and has largely been targeted at high value dessert bananas (Moreau and Le Bourdelles 1963, Beugnon and Champion 1966, Lassoudière 1978, Avilán *et al*. 1982). Moreover, few studies have been carried out on field-grown plants because traditional methods of root assessment under field conditions require tedious and time-consuming excavation of whole plants (Box 1996). In banana, two man-days are indeed needed to excavate one complete adult, ready-to-harvest, *Musa* spp. plant (Blomme 2000). In addition, excavation is destructive and thus complicates a dynamic assessment of root growth. Root measurement techniques that are non-destructive, quick and efficient, and provide insight into root dynamics, are critical for understanding environmental effects on root development. In addition, they constitute a good basis for investigating genetic differences among a large number of cultivars.

An alternative to field assessment of root systems of adult plants could be the evaluation of juvenile plants in the nursery, provided that there is a good correlation between the root system size at the two developmental stages. Swennen *et al*. (1986) evaluated juvenile *Musa* spp. plants grown under hydroponic conditions and were able to demonstrate large differences in root development between different genotypes. However, root growth in this artificial medium may differ from that of field-established plants. Furthermore, plants in hydroponics cannot be grown to their adult stage. The same restriction occurs in rhizotrons as described by Lavigne (1987). Hence, it is not known whether root measurements from juvenile plants adequately reflect root characteristics of adult plants.

A second alternative to the field assessment of entire root systems could be through indirect determination of root traits from shoot growth. Indeed, root and shoot growth are highly related in many plants such as in cotton (*Gossypium hirsutum* L.), pea (*Pisum sativum* L.), carrot (*Daucus carota* L.), turnip (*Brassica rapa* L.), palm species [*Roystonea regia* (HBK.) O.F. Cook, *Coco nucifera* L., *Syagrus romanzoffiana*

(Chamisso) Glassman and *Phoenix roebelenii* O'Brien] and strawberry (*Fragaria xananassa* Duch.) (Pearsall 1927, Broschat 1998, Fort and Shaw 1998). Russell (1977) mentioned that nodal root development in the cereals winter wheat (*Triticum aestivum* L.) and pearl millet (*Pennisetum glaucum* L.) could be estimated from the number of leaves. Henderson *et al.* (1983) found that the extent of root branching was very regular for Sitka spruce and could be estimated from the aboveground stem diameter. Smith (1964) reported that root size of Douglas fir, lodgepole pine and other British Columbia tree species could be estimated from aboveground measurements. In banana, Swennen (1984) and Blomme and Ortiz (1996) established positive correlations between root traits and aboveground plant characteristics, while Gousseland (1983) found that the number of cord roots of the 'Giant Cavendish' dessert banana can be estimated from the leaf area. This indicates that root growth is linked to shoot growth in banana, but environmental or developmental influences were not investigated.

Root sampling constitutes a third alternative to quickly estimate the total root size. Fort and Shaw (1998) found substantial correspondence between variability for soil core samples and whole-plant root mass of strawberry, indicating that changes in the root system growth can be effectively estimated from soil cores. Soil core samples required no more than 10% of the time to collect and process the entire plant root system. It is not clear whether this approach is applicable to plantain and bananas.

Research in carrot, maize, oats, onion, sunflower and tomato showed that root mass can be indirectly estimated from the plant's capacitance value (Chloupek 1972, Chloupek 1977, Dalton 1995, Van Beem *et al.* 1998). As the *Musa* plant tissue contains a lot of water, thus securing a high electrical conductivity, the potential of this root assessment method was investigated.

Banana and plantain agronomy and breeding stand to gain a lot from improved knowledge of root growth and development. Since excavation of entire root systems is laborious, destructive and provides non-dynamic insights, methods that are fast, easy to execute and that can be repeated over time on a same plant are needed. Therefore, the objectives of this study were to determine (i) the relationships between juvenile and adult root size, (ii) the relationships between root size and shoot traits, (iii) the optimum core sampling method for adequate estimation of the root system size and (iv) the relationship between capacitance values and root system size.

Materials and methods

Site characteristics

Experiments were carried out at the High Rainfall station of the International Institute of Tropical Agriculture at Onne (4°42' N, 7°10' E, 10 m altitude above sea level) in southeastern Nigeria. The station is located in a degraded rainforest-swamp. Annual rainfall is 2400 mm, unimodal and distributed from February until November. The soil is derived from coastal sediments. It is a deep and freely drained Typic Paleudult/ Haplic Acrisol (FAO/ISRIC 1998) of the coarse-loamy, siliceous isohyperthermic family. Nutrient status is poor, except for P, and pH is low (pH 4.3 in 1:1 H_2O in the upper 15 cm). Detailed characteristics of the station have been described elsewhere (Ortiz *et al*. 1997).

Agronomic practices

All fields had been under eight years of grass fallow before no-tillage planting of Musa spp. All fields were maintained similarly and this included the nematicide Nemacur application (a.i. fenamiphos) at a rate of 15 g/plant (3 treatments/year). In addition, fertilization was done with muriate of potash (50% K) at a rate of 600g/plant/year, and urea (46% N) at a rate of 300 g/plant/year, split over 6 equal applications during the rainy season. No mulch was applied. Furthermore, the fungicide Bayfidan (a.i. triadimenol) was applied 3 times/yearat a rate of 3.6 ml/plant to reduce black Sigatoka (Mycosphaerella fijiensis Morelet).

Early root screening

Three experiments were carried out. The first and second experiment involved, respectively, *in vitro* micro-propagated and sucker-derived plants of eight polyploid genotypes (Table 1) including the dessert bananas 'Yangambi km 5' and 'Valery' (AAA group), the plantain 'Obino l'ewai' (AAB group), the cooking bananas 'Cardaba' and 'Fougamou' (ABB group), the plantain-derived hybrids 'PITA2' and 'PITA7', and the cooking banana hybrid 'FHIA-03' (Swennen 1990b, Daniells *et al.* 2001). The third experiment involved *in vitro*-derived plants of 8 diploid accessions (Table 1), namely, 'Niyarma yik', 'Calcutta 4', 'Pahang', 'Pisang jari buaya', 'Pisang madu', 'Tjau lagada', 'Kisubi' and 'Pisang Berlin'. Micropropagated plants were produced following standard shoot-tip culture techniques (Vuylsteke 1989 and 1998). The plantlets were acclimatized for 6 weeks in a greenhouse nursery (Vuylsteke 1998, Vuylsteke and Talengera 1998), before field transplantation in May and June 1996, for the first and third experiment, respectively. In the second experiment, suckers were prepared as recommended by Swennen (1990a) and field planted in June 1996.

The experimental layout was a split plot within a randomized complete block design with two replications of two plants per genotype. Main plot treatments consisted of different times of observation. In the first and third experiment, data were collected from 6-week-old nursery plants, while field measurements were done on 12, 16 and 20-week-old plants, and at bunch emergence. In the second experiment, measurements were carried out in the field on plants aged 6, 12, 16 and 20 weeks, and at bunch emergence. Subplot treatments consisted of genotypes. Plant spacing in the field was 2 m x 2 m, except for plants evaluated at bunch emergence, which were spaced 4 m x 4 m to avoid root entanglement between neighbouring plants. The fields were irrigated during the dry season at a rate of 100 mm per month.

Data collection was carried out on the following corm and root characteristics: corm fresh weight (CW, g), corm height (CH, cm), widest width of the corm (WW, cm), number of suckers (NS) on the corm, number of adventitious or cord roots (NR), cord root length (LR, cm), the average diameter of cord roots at their base (AD, mm), and root dry weight (DR, g). The cord root length was measured using the line intersect method (Tennant 1975), while the diameter of the root was measured with Vernier calipers.

Estimating root traits from shoot traits

Twenty-seven genotypes representing the various *Musa* genome and ploidy groups were assessed in this experiment (Table 1). The planting material was obtained through meristem culture using the methods of Vuylsteke (1989 and 1998). Field transplanting

Table 1. Name, genome/parentage, ploidy level, type and suckering behavior of genotypes evaluated for rooting.

Name	Genome parentage	Ploidy level	Type	Suckering behaviour#	ES*	MR	SC	CM
'Niyarma yik'	AA	2	*Musa acuminata* ssp. *banksii*	Inhibited	3	X		
'Calcutta 4'	AA	2	*Musa acuminata* ssp. *burmannica*	Non-regulated	3	X	1	X
'Pahang'	AA	2	*Musa acuminata* ssp. *malaccensis*	Non-regulated	3	X		
'Pisang jari buaya'	AA	2	*Musa acuminata* ssp. *microcarpa*	Regulated	3	X		
'Pisang madu'	AA	2	*Musa acuminata* ssp. *microcarpa*	Regulated	3	X		
'Tjau lagada'	AA	2	*Musa acuminata* ssp. *microcarpa*	Regulated	3	X		
'Kisubi'	AB	2	Dessert banana	Regulated	3	X		
'Pisang Berlin'		2	Diploid indeterminate group	Regulated	3	X		
TMB2x 9128-3	AA x AA	2	Hybrid (Tjau lagada x Pisang lilin)	Non-regulated		X	2	
TMB2x 5265-1	AA x AA	2	Hybrid (Tjau lagada x Calcutta 4)	Non-regulated		X		
TMP2x 1297-3	AAB x AA	2	Plantain hybrid (Agbagba french reversion x Calcutta 4)	Non-regulated		X		
TMP2x 2829-62	AAB x AA	2	Plantain hybrid (Bobby tannap x Calcutta 4)	Non-regulated			2	
'Pisang M. hijau'	AAA	3	Dessert banana	Regulated		X		
'Yangambi km5'	AAA	3	Dessert banana	Non-regulated	1&2	X		X
'Valery'	AAA	3	Dessert banana	Regulated	1&2	X		X
'Rajapuri' India	AAB	3	Dessert banana	Regulated		X		
'Obino l'ewai'	AAB	3	Plantain	Inhibited	1&2	X		X
'Bobby tannap'	AAB	3	Plantain	Inhibited		X		
'Mbi egome'	AAB	3	Plantain	Regulated			1	X
'Muracho'	AAB	3	Starchy banana	Regulated		X		
'Mysore'	AAB	3	Dessert banana	Regulated		X		
'Pisang awak'	ABB	3	Cooking banana	Regulated		X		
'Foulah 4'	ABB	3	Cooking banana	Regulated		X		
'Cardaba'	ABB	3	Cooking banana	Regulated	1&2	X		X
'Fougamou'	ABB	3	Cooking banana	Regulated		X		X
IC 2	AAAA	4	Dessert banana	Regulated		X		
TMP4x 1621-1	AAB x AA	4	Plantain hybrid (Obino l'ewai x Calcutta 4)	Regulated		X		
TMP4x 548-9	AAB x AA	4	Plantain hybrid (Obino l'ewai x Calcutta 4)	Regulated	1&2	X		X
TMP4x 5511-2	AAB x AA	4	Plantain hybrid (Obino l'ewai x Calcutta 4)	Inhibited		X		
TMP4x 1658-4	AAB x AA	4	Plantain hybrid (Obino l'ewai x Pisang lilin)	Regulated	1&2			X
FHIA-03	ABB x AA	4	Cooking banana hybrid (SH-3386 x SH-3320)	Regulated	1&2			X

* CM: Capacitance Method, ES: Early Screening method, MR: Multiple Regression method, SC: Soil Core method. Within the methods, numbers show the experiment number in which the method was used. #: Suckering behaviour is inhibited when suckers do not grow fast until flowering of the parent plant; is regulated if 1-3 suckers grow very well before flowering; is non-regulated if almost all suckers grow well before flowering.

was done in June 1996 at a spacing of 2 m x 2 m. The experimental design was a randomized complete block with two replications of two plants per genotype. Shoot and root traits were assessed during mid-vegetative growth (i.e. 20-week-old plants). Shoot growth characteristics included plant height (PH, cm), circumference of the pseudostem at soil level (PC, cm), height of the tallest sucker (LS, cm), number of leaves (NL) and leaf area (LA, cm2). Leaf length and maximum leaf width were measured and LA was calculated according to Obiefuna and Ndubizu (1979). The corm and roots were completely dug out and assessed as described above. Total cord root length (TL, cm) of the mat (i.e. main plant and suckers) and total root dry weight of the mat (TD, g) were also measured. The tallest sucker was separated from the main plant and the same characteristics as above were measured.

Core sampling

In the first experiment, the small French plantain 'Mbi egome' (Swennen 1990b) and the wild diploid banana 'Calcutta 4' were assessed (Table 1). 'Calcutta 4' has a non-regulated suckering (all suckers grow simultaneously), while 'Mbi egome' has a regulated suckering behaviour (one or two suckers grow vigorously). Sucker-derived plants of 'Mbi egome' and *in vitro*-derived plants of 'Calcutta 4' were field established in August 1997. Suckers were prepared and planted according to Swennen (1990a). *In vitro*-derived plants of Calcutta 4 were grown in polybags for 6 weeks in the greenhouse before field planting. Plant spacing was 4 m x 4 m. In the second experiment, 30 progenies from a cross between two diploid hybrids, 'TMB2 x 2829-62' and 'TMB2 x 9128-3' were assessed (Table 1). Micro-propagated plants were obtained, as in experiment one, and were established in the field during August 1996 at a spacing of 3 m x 2 m. In both experiments, treatments were completely randomized.

Sixty-week-old mats were assessed in experiment one. Eight soil core samples were taken at 15 cm from the plant base. The first sample was taken near the biggest sucker and where the future axial sucker would emerge. Subsequent samples were taken clockwise at 45° intervals. Soil cores had 25 cm diameter and a 80 cm height. Soil cores were taken with a metal cylinder. Samples were washed to free roots from soil and the following characteristics were measured for each sample: number of adventitious or cord roots (NR), root dry weight (DR, g) and cord root length (LR, cm). The same characteristics were measured for the entire plant, which was excavated after core sampling. In the second experiment, root assessment was carried out as in experiment one but in July 1999 on 3-year-old mats. Three soil cores were taken per plant including the position next to the tallest sucker and at 90° and 180° clockwise from the tallest sucker.

Capacitance measurements

Measurements were carried out on *in vitro* and sucker-derived plants of different ages (Table 1). Variability in capacitance values was assessed according to the position of the electrodes (Figure 1). The soil-based positive electrode was placed at different soil depths and distances from the plant. The negative electrode was inserted in the pseudostem at variable heights and depths. Also the influence of corm size, soil temperature and water content on capacitance was investigated.

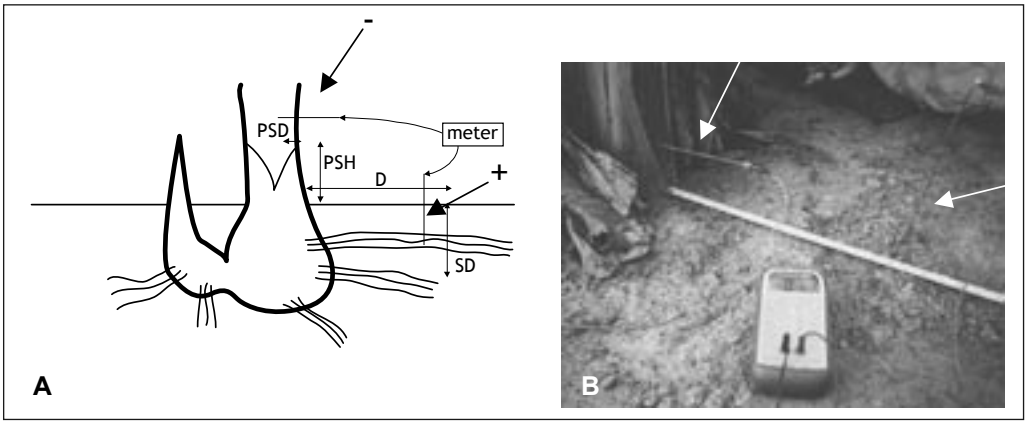

Figure 1. (A) Traits defining the position of both electrodes (PSH: Pseudostem Height, PSD: Pseudostem Depth, D: Distance from the pseudostem, SD: Soil Depth); (B) Measuring the capacitance; the arrows indicate the electrodes.

Statistical analysis

Statistical analysis was carried out using the SAS statistical package (SAS 1989). For the early screening experiments, simple Pearson correlation coefficients between identical root growth characteristics of plants at different ages across genotypes were calculated. Simple correlation and multiple regression analyses were used to estimate the relationships between aerial growth and root system characteristics. Regression was carried out using stepwise selection with root characteristics as dependent variables and shoot traits as independent variables. Ploidy level was also included as an independent variable in the regression analysis.

Data from the core sampling experiments were subjected to ANOVA to determine the effects of plant and sampling location on soil core root characteristics. Root characteristics of the core samples were regressed on whole plant root traits. Data from the capacitance experiments were subjected to ANOVA to determine the effects of the position of the electrodes on the capacitance values. To find relationships between the capacitance values and the root parameters, scatter plots and linear correlation analyses (Proc CORR in SAS) were carried out on the complete data set but also according to the type of planting material and the age of the plants.

Results and discussion

Early root screening

Few significant correlations were observed for corm and root traits between the different growth stages of diploid, triploid and tetraploid genotypes in all three experiments (Tables 2 and 3). Significant positive correlations were mostly observed for *in vitro*-derived plants. There were very few correlations for the traits considered in all three experiments between plants at 6 weeks after planting and plants in the mid-vegetative stage (*i.e.* 20 weeks old) or plants at bunch emergence. An increased difference in plant age reduced the number of significant correlations (Tables 2 and 3). Absence of significant correlations with sucker-derived plants might be attributed to differences in

Table 2. Correlation coefficients between identical growth characteristics at different ages for *in vitro* and sucker-derived triploid and tetraploid plants.

	Trait #										
in vitro	**CW**	**CH**	**WW**	**DR**	**NR**	**LR**	**AD**	**TD**	**TL**	**LS**	**NS**
6,12 (1)	na	na	na	0.34	0.22	0.38	0.39	0.34	0.37	na	na
6,16	na	na	na	0.22	0.61	0.12	0.4	0.08	-0.02	na	na
6,20	na	na	na	0.41	0.13	0.20	0.05	0.22	0.1	na	na
6,Fl (2)	na	na	na	0.75*	0.57	0.30	0.03	0.18	-0.3	na	na
12,16	0.17	0.15	0.49	0.71*	0.26	0.47	0.56	0.66	0.5	0.58	0.47
12,20	0.27	0.52	0.34	0.87**	-0.03	0.60	0.46	0.91**	0.81*	0.64	0.1
12,Fl	-0.32	-0.33	-0.18	0.07	-0.18	-0.45	0.24	0.12	-0.22	-0.03	0.27
16,20	-0.18	-0.03	-0.01	0.62	0.35	0.58	0.73*	0.70	0.6	0.98***	0.89**
16,Fl	0.22	0.34	0.03	-0.05	0.29	0.18	0.06	0.33	0.42	0.45	0.87**
20,Fl	0.07	-0.07	-0.22	0.37	0.39	-0.16	0.26	0.41	-0.07	0.42	0.87*
Sucker-derived	**CW**	**CH**	**WW**	**DR**	**NR**	**LR**	**AD**	**TD**	**TL**		
6,12	-0.10	-0.30	0.03	-0.18	-0.06	0.07	0.14	-0.18	0.07		
6,16	0.44	0.60	0.11	0.46	0.55	0.40	-0.23	0.46	0.40		
6,20	-0.22	-0.52	-0.69	0.32	-0.10	0.20	0.39	0.32	0.20		
6,Fl	0.07	0.39	-0.20	-0.40	-0.09	-0.60	0.15	-0.12	-0.37		
12,16	-0.30	-0.69	-0.10	0.22	0.17	0.41	-0.22	0.22	0.41		
12,20	0.40	0.48	-0.53	-0.47	-0.20	-0.20	-0.31	-0.47	-0.20		
12,Fl	0.36	0.13	0.29	0.29	-0.65	-0.18	-0.50	0.42	0.08		
16,20	0.03	-0.19	-0.10	0.64	0.10	0.68	0.15	0.64	0.68		
16,Fl	-0.35	-0.21	-0.67	0.35	0.13	-0.78*	0.01	0.79*	0.21		
20,Fl	0.33	-0.06	0.09	0.33	0.04	-0.32	0.67	0.52	0.32		

#: AD: average basal cord root diameter (mm), CH: corm height (cm), CW: corm fresh weight (g), DR: root dry weight (g), LR: cord root length (cm), LS: height of the tallest sucker (cm), NR: number of cord roots, NS: number of suckers, TD: total root dry weight of the mat (g), TL: total length of the cord roots of the mat (cm), WW: corm widest width (cm)

*, **, *** Significant at P<0.05, 0.01 and 0.001, respectively

(1): 6,12: correlation between plants aged 6 and 12 weeks, (2) Fl: at flower emergence

na: not applicable.

physiological age of the suckers at planting, which influenced subsequent growth. In addition, large genotypic variation exists for vegetative growth cycle and plant size at bunch emergence (Swennen and Vuylsteke 1987), which may explain the absence of correlations between root growth during the early vegetative stage and early reproductive stage in both propagule types. We conclude that the root characteristics of adult plants cannot be estimated from the root size of juvenile plants irrespective of the type of planting material.

Estimating root traits from shoot traits

Significant correlation coefficients between aerial and root system characteristics were found during vegetative development (Table 4) confirming earlier reports (Beugnon and Champion 1966, Gousseland 1983, Swennen 1984, Lavigne 1987, Blomme and

Table 3. Correlation coefficients between identical growth characteristics at different ages for *in vitro*-derived diploid plants.

	Trait #										
in vitro	CW	CH	WW	DR	NR	LR	AD	TD	TL	LS	NS
6,12 (1)	na	na	na	-0.48	-0.37	-0.25	0.79*	-0.48	-0.25	na	na
6,16	na	na	na	-0.09	-0.27	-0.18	0.33	-0.22	-0.25	na	na
6,20	na	na	na	0.38	0.56	0.52	0.11	0.36	0.46	na	na
6,Fl (2)	na	na	na	-0.03	-0.76*	-0.42	0.05	-0.26	-0.40	na	na
12,16	0.61	0.53	0.65	0.46	0.64	0.80*	0.68	0.62	0.85*	-0.24	0.11
12,20	0.25	0.66	-0.01	0.13	0.22	0.36	-0.42	0.31	0.45	-0.67	0.48
12,Fl	0.01	-0.09	0.17	0.17	-0.20	-0.35	0.40	0.37	-0.16	-0.06	0.91**
16,20	0.05	0.76*	-0.22	0.41	0.36	0.73*	-0.13	0.47	0.80*	0.77*	0.13
16,Fl	-0.12	-0.03	0.01	0.37	0.03	0.09	0.06	0.15	0.14	0.43	0.02
20,Fl	0.40	-0.43	0.47	0.19	0.04	0.10	-0.15	0.44	0.27	0.48	0.44

AD: average basal cord root diameter (mm), CH: corm height (cm), CW: corm fresh weight (g), DR: root dry weight (g), LR: cord root length (cm), LS: height of the tallest sucker (cm), NR: number of cord roots, NS: number of suckers, TD: total root dry weight of the mat (g), TL: total length of the cord roots of the mat (cm), WW: corm widest width (cm)

*, **, *** Significant at P<0.05, 0.01 and 0.001, respectively

(1): 6,12: correlation between plants aged 6 and 12 weeks, (2) Fl: at flower emergence

na: not applicable.

Table 4. Correlation coefficients (P<0.05) between aerial growth and root system characteristics at 20 weeks after planting.

Trait #	**LA**	**PH**	**PC**	**LS**
DR	0.72***	0.65***	0.65***	-0.09
NR	0.46*	0.41*	0.29	0.16
LR	0.64***	0.54**	0.46*	0.08
AD	0.47*	0.51**	0.70***	-0.38*
TD	0.65***	0.53**	0.38	0.2
TL	0.41*	0.25	0.01	0.49*

#: AD: average basal cord root diameter (mm), DR: root dry weight (g), LA: leaf area (cm2), LR: cord root length (cm), LS: height of the tallest sucker (cm), NR: number of cord roots, PC: plant circumference (cm), PH: plant height (cm), TD: total root dry weight of the mat (g), TL: total length of the cord roots of the mat (cm)

*, **, *** Significant at P<0.05, 0.01 and 0.001, respectively.

Ortiz 1996). Similar relationships between root and shoot traits were also found for the East African highland bananas (AAA-EA group) (Sebuwufu *et al*. 2004). Furthermore, regression analysis produced several equations (Table 5) that attributed at least 90% of the variation in root growth to variation in shoot development. The best shoot indicators of root growth were leaf area, pseudostem circumference and height of the tallest sucker. Swennen (1984) already demonstrated that ratooning can be improved by increasing rooting of the parent plant.

These regression models suggest that a reduced leaf area, as caused by black Sigatoka, will adversely affect root development. Hence increased (photosynthetically active) leaf area (from optimal plant spacing, thereby reduced shading) and improved nutrient

Table 5. Regression models to predict root system characteristics at 20 weeks after planting using aerial growth characteristics and ploidy level as independent variables.

	Trait # (Independent variables)				
Trait #	**LA**	**PC**	**LS**	**PL**	**R2**
DR	0.00163***	0.596**			0.93
NR	0.00146***	1.255***			0.93
LR	0.0667***	23.47**	0.94		
AD		0.0938***		0.681***	0.97
TD	0.00207***	0.426	0.171*		0.93
TL	0.0995***		14.69***		0.92

#: AD: average basal cord root diameter (mm), DR: root dry weight (g), LA: leaf area (cm^2), LR: cord root length (cm), LS: height of the tallest sucker (cm), NR: number of cord roots, PC: plant circumference (cm), PL: ploidy level, TD: total root dry weight of the mat (g), TL: total length of the cord roots of the mat (cm)

^: independent variables

*, **, *** Significant at P<0.05, 0.01 and 0.001, respectively.

status of the plant would stimulate root development. Indeed roots are sinks for assimilates that need to come from functional leaves. The pseudostem is made up of leaf sheaths and hence reflects the number of leaves and plant vigour. Plant pseudostem circumference thus reflects shoot growth and is an important determinant of root vigour in the regression models.

The size of the tallest sucker reflected positively the extent of the mat root system. Most suckers observed on 20-week-old plants were peepers (*i.e.* small sucker with scale leaves) or sword suckers (*i.e.* larger sucker with lanceolate leaves). The latter suckers have their own root system, confirming observations by Robin and Champion (1962) and Beugnon and Champion (1966). The observed positive effect of ploidy on cord root diameter confirms earlier observations by Monnet and Charpentier (1965).

Shoot-to-root ratios depend on the developmental stage of a plant (Brouwer 1966). In banana, Gousseland (1983) estimated cord root number from leaf area and reported an effect of plant developmental phase on the accuracy of the regression model. He reported that the number of cord roots is underestimated during the early vegetative phase. Shoot-to-root ratios also vary across environments (Brouwer and De Wit 1969, Squire 1993, Martinez Garnica 1997, McMichael and Burke 1998, Blomme 2000). Refinement of the regression equations is needed by taking account of the plant developmental stage and environmental conditions. In conclusion *Musa* root system development can be estimated from easily measurable above ground characteristics. This provides a fast and non-destructive assessment of root development.

Core sampling

Most roots of the assessed mats were observed within a 60 cm radius from the plant and up to 70 cm depth. For the first experiment, data on root characteristics obtained through soil core sampling involved about 1.1 to 2.6% of the total root system, depending on the root trait under consideration (Table 6). For 'Calcutta 4', a significant inter-plant effect was observed for the dry weight, number and length of the roots present in soil cores (Table 7). This can be explained by the high variability in mat root system size (Table 6). However, no significant differences were observed for sampling

Table 6. Mean and coefficient of variation for different root (whole mat and soil core) characteristics for 60 weeks old 'Calcutta 4' and 'Mbi egome' mats.

		Genotype			
		Calcutta 4		Mbi egome	
Trait #		Mean	CV (%)	Mean	CV (%)
DR	Whole mat	262.9	37	336.0	43
	Soil core	2.9	71	4.4	56
	Soil core/Whole mat (%)	1.1	66	1.4	52
NR	Whole mat	491.0	22	465.5	22
	Soil core	13.0	49	11.5	44
	Soil core/Whole mat (%)	2.7	44	2.5	44
LR	Whole mat	10809.2	31	10200.0	26
	Soil core	238.1	47	259.5	40
	Soil core/Whole mat (%)	2.2	36	2.6	37

#: DR: root dry weight (g), NR: number of cord roots, LR: cord root length (cm).

Table 7. Mean squares and significance for different soil core root characteristics for 60 weeks old 'Calcutta 4' and 'Mbi Egome' mats.

			Trait #		
Genotype	Source of variation	df	DR	NR	LR
Calcutta 4	Plant	10	16.0***	141.0***	55,998***
	Sampling location	7	2.17	25.92	7661
	Residual	70	2.70	28.30	6981
Mbi egome	Plant	11	15.31***	34.33	25,642***
	Sampling location	7	19.65***	52.78*	23,683**
	Residual	77	3.61	20.89	7,244

#: DR: root dry weight (g), NR: number of cord roots, LR: cord root length (cm)
*, **, *** Significant at P<0.05, 0.01 and 0.001, respectively.

location within a plant (Table 7). This could be due to the high number of well-developed suckers uniformly spaced around the main plant. Significant inter-plant differences in root characteristics were also observed for 'Mbi Egome', but the effects of sampling location were even more important (Table 7), which may be explained by the regulated suckering behavior (*i.e.* development of 1-3 large suckers on the plant) of this cultivar causing sucker root systems to be less uniformly distributed around the main plant.

Root dry weight, number and length of the cord roots in the core samples were regressed on the corresponding characteristics from the mat. All models were significant at $p<0.01$, with $R^2 \geq 0.58$, 0.73 and 0.81 for regressions based on 1 or 2 (Table 8), or 3 core samples (data not shown), respectively. Sampling locations nearest to the tallest sucker did not increase R^2 values (Table 8). Data from the second experiment also revealed large differences attributable to variation in suckering behavior among the 30 genotypes assessed. However, this did not appear to affect the regression of core samples on whole plants for root size estimation. The lowest R^2 values were obtained with single core samples and were respectively 0.71, 0.81 and 0.78 for root dry weight,

Table 8. R^2 values for root dry weight, cord root number and cord root length, of regressions between one (A)/two (B) soil core sample(s) and whole mat samples for 60 weeks old 'Calcutta 4' and 'Mbi egome' mats.

A											
Genotype	Trait #	Sample No. (1)									
		1	2	3	4	5	6	7	8		
Calcutta 4	DR	0.73	0.79	0.81	0.80	0.88	0.58	0.78	0.92		
	NR	0.90	0.91	0.86	0.78	0.93	0.83	0.80	0.86		
	LR	0.94	0.90	0.92	0.83	0.95	0.88	0.90	0.95		
Mbi egome	DR	0.73	0.75	0.88	0.68	0.79	0.79	0.94	0.87		
	NR	0.79	0.86	0.93	0.73	0.84	0.95	0.98	0.83		
	LR	0.89	0.90	0.90	0.84	0.91	0.96	0.98	0.91		
B		Sample No.									
		1,2	1,3	1,4	1,5	1,6	1,7	1,8	2,3	2,4	2,5
Calcutta 4	DR	0.82	0.85	0.80	0.85	0.82	0.85	0.88	0.86	0.87	0.90
	NR	0.95	0.94	0.88	0.94	0.95	0.91	0.94	0.89	0.92	0.96
	LR	0.96	0.97	0.93	0.97	0.97	0.96	0.97	0.92	0.93	0.97
Mbi egome	DR	0.82	0.90	0.79	0.86	0.80	0.95	0.91	0.87	0.80	0.79
	NR	0.90	0.94	0.85	0.89	0.90	0.97	0.92	0.96	0.89	0.87
	LR	0.95	0.96	0.92	0.95	0.94	0.99	0.97	0.94	0.92	0.93
		2,6	2,7	2,8	3,4	3,5	3,6	3,7	3,8	4,5	
Calcutta 4	DR	0.81	0.83	0.89	0.84	0.91	0.89	0.88	0.94	0.91	
	NR	0.94	0.90	0.92	0.87	0.94	0.92	0.88	0.90	0.90	
	LR	0.95	0.93	0.96	0.92	0.96	0.96	0.95	0.97	0.94	
Mbi egome	DR	0.83	0.93	0.90	0.88	0.88	0.89	0.94	0.90	0.80	
	NR	0.95	0.98	0.93	0.92	0.96	0.98	0.97	0.91	0.88	
	LR	0.96	0.97	0.98	0.94	0.95	0.97	0.96	0.94	0.94	
		4,6	4,7	4,8	5,6	5,7	5,8	6,7	6,8	7,8	
Calcutta 4	DR	0.87	0.89	0.96	0.79	0.87	0.93	0.73	0.84	0.92	
	NR	0.91	0.88	0.93	0.92	0.92	0.94	0.87	0.92	0.87	
	LR	0.96	0.96	0.97	0.94	0.95	0.98	0.91	0.96	0.95	
Mbi egome	DR	0.79	0.93	0.84	0.84	0.92	0.88	0.93	0.88	0.93	
	NR	0.90	0.94	0.85	0.94	0.97	0.92	0.99	0.95	0.94	
	LR	0.94	0.97	0.92	0.96	0.97	0.98	0.98	0.97	0.97	

number of cord roots and cord root length (Table 9). At least 80% of the variation in mat root traits could be explained by taking two core samples, while 85% could be explained with three core samples.

Table 9. R^2 values for root dry weight (DR), cord root number (NR) and cord root length (LR), of regressions between single, double and triple soil core samples and the whole mat samples for 30 progenies from a cross between 'TMPx 2829-62' and 'TMPx 9128-3'.

	Sample No. (1)						
Trait #	1	2	3	1,2	1,3	2,3	1,2,3
DR	0.78	0.80	0.71	0.86	0.81	0.80	0.85
NR	0.86	0.86	0.81	0.91	0.87	0.89	0.90
LR	0.85	0.86	0.78	0.91	0.85	0.88	0.89

#: DR: root dry weight (g), NR: number of cord roots, LR: cord root length (cm)

(1) Sample 1 corresponds to site of the future axial sucker; the following samples are taken clockwise around the parent plant at 45 degree intervals.

The results from both experiments indicate that mat root system characteristics can be adequately estimated from two soil core samples. Moreover, root samples collected from two soil cores requires only 5% of the time needed to excavate and measure the entire root system of an adult *Musa* plant.

Capacitance measurements

Distance of the soil-based electrode from the plant had no significant effect on capacitance readings (Table 10). In contrast, soil depth, pseudostem height and insertion depth, soil temperature and water content had a significant effect on capacitance. Very few significant correlations between capacitance values and root system traits were found. The specific morphology of the banana plant might be the cause. For example, the enclasping leaf sheaths with their numerous air spaces that make up the pseudostem and the underground corm (*i.e.* the real stem) with many suckers, might influence the capacitance readings. Therefore root system traits of juvenile and adult field-grown *Musa* spp. plants cannot yet be estimated through capacitance measurements.

In conclusion, root systems can best be assessed from shoot measurement and root core sampling as both methods are fast, easy to execute and can be repeated over time on the same plant. Hence a dynamic picture on root development can be developed. Both methods however are location specific.

Table 10. Mean square and significance tests for the capacitance value.

Source of variation #	df	Mean square for capacitance
PSH	1	0.325***
PSD	2	0.784***
D	2	0.0057
SD	3	0.590***

#: PSH: pseudostem height, PSD: pseudostem depth, D: distance from the pseudostem, SD: soil depth. *, **, *** Significant at P<0.05, 0.01 and 0.001, respectively.

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