Dynamics of Root Growth and Distribution in Maize from the Black Soil Region of NE China

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Abstract

Root growth is related to its water and mineral uptake. The structure and architecture of the root system is influenced by soil properties. Better understanding of root architecture and growth dynamics of maize grown on black soil may lead to more efficient use of applied nutrients and water by maize. Maize (*Zea mays* L.), cultivar Yedan 13, was grown in a black soil field in large root boxes in 2007. Plants were regularly sampled and the following data were recorded: number of emerged roots per phytomer, mean length and maximal length of axile root per phytomer, maximum rooting depth of axile root per phytomer, and angle of axile root per phytomer by excavation methods. The distribution dynamics of root dry weight at different black soil depths, and vertical and horizontal distribution in large root boxes were measured. There were more axile roots on the upper phytomers than on lower phytomers. The number of roots on phytomers P8, P9 and P10 were 15.71%，24.82%, and 25.86% of total number of per plant, respectively. Angles of the axile roots on lower phytomers were larger than those on upper phytomers. The angle of the axile root on P2 was the largest (81.51°), followed by P4 (69.33°), P3 (56.9°), and P5 (56.06°). The angles on phytomers from P6 to P10 were smaller, ranging from 30.13-40.72°. Mean length, maximal length, and maximum rooting depth of axile root on each phytomer all increased with day after seeding (DAS). Mean length, maximal length, and maximum rooting depth of axile roots on lower phytomers were larger

than those on upper phytomers. Mean length, maximal length and maximum rooting depth of axile roots on P3 were the largest (2.37 m, 2.92 m and 2.12 m at 90 DAS, respectively). Root dry weight in each soil layer increased with DAS; there was a rapid increase from 50 to 90 DAS. About 80 % of root dry weight was in the soil above 40 cm. The general trend of percentage of dry weight in total dry weight per plant decreased as the distance from the plant increased. Over 78 % of root dry weight in total dry weight per plant was within 20 cm in the horizontal direction from the plant, and less than 6% was in the 40 cm to 60 cm zone in the horizontal direction from the plant.

Key words: Root distribution, Root box, Axile root, Root morphology, *Zea mays* L.

1. Introduction

Maize has a fibrous root system comprising embryonic and post-embryonic roots, which are emitted from the bottom part of the successive phytomers. The embryonic root system is made up of the primary root and a variable number of seminal roots (Abbe and Stein, 1954). Later in development, the post-embryonic shoot-borne root system becomes dominant (Hochholdinger et al., 2004a). The maize rootstock has a unique architecture, which ensures the efficient uptake of water and nutrients, and provides anchorage (Aiken & Smucker, 1996; Hetz et al., 1996; Lynch, 1995).

The structure and architecture of the root system is related to its water and mineral uptake (Pagès & Pellerin, 1994). The establishment of the basic architecture of the root system is an important prerequisite for these functional requirements (Hochholdinger et al., 2004b). Recently, great progress has been made on discerning the relationship between the structure and the nutrient uptake of individual roots (Clarkson, 1991; Fitter, 1991; Pagès & Pellerin, 1994).

Root architecture is very complex and dynamic in nature. The structure of the root system is shaped by an endogenous genetic program, as well as by external factors perceived from the biotic and abiotic environment (McCully, 1995; McCully, 1999). Variability of root formation in response to environmental conditions complicates the identification of genetic components involved in root formation (Hochholdinger et al., 2004b). Both genetic and environmental factors affect the growth direction of maize nodal roots (Nakamoto et al., 1991; Tardieu & Pellerin, 1990; Tardieu & Pellerin, 1991; Eghball et al., 1993; Costa et al., 2001). Soil environment is dynamic in nature, and its influence on plant growth, and consequently on root growth, is complex. Root growth is influenced by the physical, chemical, and biological properties of soil (Fageria et al., 2006).

The black soils, with thick humic horizons, possess good physical, chemical, and biological properties (Zhang et al., 2006). The area of the black soil region of NE China is 5.956×10^6 hm^2 (Meng et al., 2003), of which the ploughed land area is 4.438×10^6 hm^2. It is an important region for producing commercial farm products and food. The yield and export of maize of Northeast China accounted for 1/3 and 1/2 of the national total, respectively (Sui et al., 2005). Many works have emphasized the need to describe the root system architecture to provide a basis for improved understanding of the uptake of water and minerals (Clarkson, 1991). Under field conditions, the physical and chemical properties vary widely within a soil profile, and information about maize root architecture and growth dynamics as a function of environmental factors is scattered and not often readily accessible. However, the root box study provides a physically and chemically uniform soil environment to replicate plants and is highly reproducible.

In the present study, we constructed large root boxes to study the root distributions of plants grown in black soil. We measured the direction of axile root growth, the maximum rooting depth, and the axile root length as important factors that determine the spatial distribution of roots in the soil. Other possible factors that may determine the distribution of the root system will also be discussed. Increased knowledge of root architecture and root development dynamics of maize on black soil is crucial for improving productivity of maize and for the more efficient use of applied nutrients and water.

Maize root system made of seminal roots and of nodal roots which are emitted at the bottom part of the successive phytomers. In the following text, the mesocotyl is considered as a first phytomer. The first tier of roots at the bottom of the stem is thus considered to belong to the second phytomer (P2). Upper tiers of roots are named roots from P3, P4 and so on (Figure 1) (Girardin et al., 1986; Sylvain, 1993). All nodal roots will be termed axile roots (Feix et al., 2002).

2. Materials and methods

2.1 Study site

The study was carried out at Agricultural Experimental Station (44°12′N, 125°33′E) of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, at Dehui City of Jilin Province, China. This study

site was in black soils (Udolls, US Soil Taxonomy) region with fertile soil and abundant water resource. The mean annual temperature is 4.4ºC and the mean annual precipitation is 520.2 mm with more than 70% occurring in June, July and August. Soil physical and chemical properties are given in Table 1.

2.2 Experimental Field and management

Maize (*Zea mays* L., cv. Yedan 13) was planted on April 27, 2007 with fertilizer consisting of N, P, and K, each at 60 kg ha^{-1}. Additional N at 56 kg ha^{-1}, as side dressed ammonium nitrate, was applied on June 25, 2007. The planting density was 55 000 plants hm^{-2}. The insects were controlled by means of pesticides. On 25 day after sowing (DAS), 40 DAS, 50 DAS, 70 DAS, and 90 DAS samples were measured from the experimental field measured. To measure the length, angle, maximum horizontal distance, and maximum rooting depth of axile roots, trenches were dug and excavated by carefully removing the surrounding soil. Axile roots were gently excavated so as not to damage them. If a root was broken in its branched zone it was discarded. Three roots types of five randomly chosen plants were measured. The length, angle, maximum rooting depth, and the maximum horizontal distance from the plant (horizontal reach) were recorded for each axile root (Liedgens and Richner, 2001). The length of axile roots was the distance between the base and the root tip. The elongation angle, which is defined as the deflection from the vertical, was measured at a point that was 0.3 m from where axile l root entered the soil (Araki et al., 2000; Pinthus, 1967). The angle of the axile root growth from the vertical was measured on three roots per plant using a protractor.

2.3 The root box experiment

Maize plants (*Zea mays* L., cv. Yedan 13) were grown in root boxes. Root boxes came in three sizes: small (1.0 m high and 0.65 m diameter), medium (1.0 m high and 0.95 m diameter), and large (1.5 high and 1.2 m diameter). Sampling was done at 25 DAS and 40 DAS from small root boxes, on 50 DAS and 70 DAS samples from medium root boxes, and on 90 DAS from the large root boxes. The root boxes were cylindrical, with galvanized sides and bases. The bases had 25 vents (0.5-1.0 cm diameter). Networks of boxes were formed by welding the boxes to eight upright posts. The network was perpendicular to the upright posts, and parallel to the bottom; the distance between adjacent networks was 5 cm and the mesh area was 7 cm^2 (Figure 2).

Soil was taken, from the topsoil downward, in 10 cm trenches, each trench being regarded as a unit. Soil from each unit soil layer was sifted through a 20.0 mm sieve. Root boxes were placed in the soil of the experimental field, with the top of the base part of the root boxes at ground level. Soil was loaded into the roof box to the corresponding depth. Each soil layer was watered after it was placed into the root box and fertilized during the next spring with fertilizer consisting of N, P, and K, each at 60 kg ha^{-1}. On April 27, 2007, four seeds were sown per root box, at a depth of 4 cm. The resulting seedlings were thinned to one per container, three days after emergence. Additional N at 56 kg ha^{-1}, as side dressed ammonium nitrate, was applied on June 25, 2007.

At sampling, root boxes were removed from the soil by carefully sliding out the entire root mass. The stem was cut off and the root system washed. The roots were first completely immersed in a water-filled root box, and then removed from the sheet iron and sprayed with water until almost free of soil. After washing, root samples were taken from each 10 cm soil layer in the vertical direction. In the horizontal direction, roots were sampled distances of 0–20 cm, 20–40 cm and 40–60 cm, each distance being the radius of a concentric circle whose center was the bottom of the stem base of the plant. Three replicate samples of the roots in each plot were oven-dried at 70 °C for 36 h, and then weighed.

2.5 Statistical analysis

The experimental data were analysed with an analysis of variance (ANOVA). Means were compared by Fisher's LSD test at the 5% level with SPSS 16.0 software (SPSS, Chicago, USA).

3. Results

3.1 Number of emerged axile roots per phytomer at different DAS

With increasing DAS, more roots emerged from each phytomer (Table 2). Fewer axile roots emerged on phytomers from P2 to P7 than on phytomers P8 to P10. Roots belonging to the same phytomer emerged at approximately the same time. After emerging from the phytomer, the number of axile roots barely changed.

3.2 Mean length and maximal length of axile roots at different DAS in the field

The mean length and maximal length of the axile roots on each phytomer increased with DAS (Table 3). Compared with mean length and maximal length of axile roots on lower phytomers, axile roots on upper phytomers were shorter.

3.3 Maximum rooting depth of axile roots at different DAS in the field

The maximum rooting depth of axile roots on each phytomer increased with DAS (Table 4). Compared with the maximum rooting depth of axile roots on upper phytomers, those on the lower phytomers were deeper.

3.4 Angles of different root types

The angles of axile roots on lower phytomers were larger than those on upper phytomers. The angle of the axile root on P2 was the largest (81.51°), followed by P4 (69.33°), P3 (56.9°), and P5 (56.06°). The angles of the axile roots on phytomers P6 to P10 were smaller, ranging from 30.13° to 40.72° (Figure 3).

3.5 Distribution dynamics of root at different DAS

Root dry weight in each soil layer is dynamic at different DAS (Table 5). Root dry weight in each soil layer increases with DAS; there was a rapid increase from 50 to 90 DAS. Early in the growing season, root dry weight was mainly distributed in the upper layer of the black soil. Roots grew gradually downward as the maize grew, increasing the root dry weight in deeper layer of the black soil.

The vertical distribution of the percentage of dry weight in each soil layer in total dry weight per plant followed a "T" pattern at different DAS (Figure 4). The general trend of percentage of dry weight in each soil layer of the total dry weight per plant significantly declined with the depth of the soil. However, in isolated cases, the percentage of dry weight in each soil layer of the total dry weight per plant in the lower soil was more than that in the upper soil. About 80 percent of root dry weight was in the soil above 40 cm, with more in the top 20 cm compared with the 20 cm to 40 cm soil layers.

The general trend of percentage of dry weight of total dry weight per plant decreased as the distance from the plant increased (Table 6). Over 78% of root dry weight in total dry weight per plant was within 20 cm along the horizontal direction from the plant; less than 6% was found in the 40 cm to 60 cm zone.

4. Discussion

Maize formed a large number of axile roots in black soil, with more axile roots in the upper phytomers compared with the lower phytomers, with P8, P9, and P10 representing 15.71%, 24.82%, and 25.86% of the total number per plant, respectively. Axile roots of the upper phytomers dominate the adult root stock and are responsible for lodging resistance (Pellerin et al., 1990) and the provision of water and nutrients for morphogenesis and the normal physiological functions of the stalk, middle and upper leaves, ear, and kernel (Hochholdinger, 2009; Zhang, 1981). The number of emerged axile roots slightly correlated with the diameter of the internode from which nodal roots emerged ($r=0.58$, $p<0.05$) (Demotes-Mainard & Pellerin, 1992) as previously reported by Demotes-Mainard and Pellerin 1992. For maize grown in black soil, the diameters of P8, P9, and P10 roots were significantly greater than those from P1 to P7 (Data not shown).

Despite its importance to the spatial distribution of roots in black soil, little attention has been given to the growth direction of nodal roots (Nakamoto, 1993). In this paper, the nodal roots on lower internodes had larger angles compared with the nodal roots on upper internodes; i.e. the nodal roots on the upper internodes grew more vertically. These results agree with those of Yamazaki and Kaeriyama (Yamazaki & Kaeriyama, 1982). The growth direction depends on the position of the internode from which nodal roots emerge, and both genetic and environmental factors affect the growth direction of maize nodal roots (Chaudhary & Prihar, 1974; Tardieu & Pellerin, 1990; Tardieu & Pellerin, 1991).

Comparing mean length with maximal length of axile roots, the difference for internodes P2 to P5 was greater than that for internodes P6 to P10 (Table 3), i.e. the length of each root on each internode from P2 to P5 varied widely. By contrast, the difference in length among roots on internodes P6 to P10 changed relatively little.

The may be because the angles of the roots on internodes P2 to P5 were greater than those on internodes P6 to P10 (Figure 3). Thus, the axile roots on lower nodes tended to grow in a horizontal orientation. In the field, the axile roots on each internode were distributed at about the same horizontal distance from the internode. Thus, axile roots at lower nodes had a larger growth space in the horizontal orientation than those on the upper nodes. Therefore, the volume of soil occupied by the axile roots on internodes P2 to P5 was larger. In other words, variations in growth potential (MacLeod, 1990) and environmental conditions led to asymmetrical distributions of the final root lengths (Cahn et al., 1989). However, the opposite was true for axile roots on internodes P6 to P10.

In this paper, the maximal length and maximum rooting depth increased with DAS (Table 3 and 4). This result was similar to that reported by Borg and Grimes (1986). This general trend decreased gradually from P2 to P10. The maximum rooting depth of axile root on internodes from P2 to P5 was larger and they went deeper into the

soil as DAS increased (Table 4); therefore, the roots in deep soil horizons increased with DAS (Table 5 and Figure 4). Under drought conditions, soil starts drying from the surface, but the deep soil horizons may remain moist and able to supply water to plant roots at later developmental stages. Consequently, deep root portions may have more effect than shallow root portions (Fageria et al., 2006). Vertical distributions of maize roots vary among cultivars and their growth conditions. However, the ecological and physiological characteristics of the deep root and the mechanisms modulating deep rooting of maize are still unknown (Hochholdinger, 2009). The dry weights of horizontal and perpendicular distributions of maize roots in black soil decreased gradually with the perpendicular distance and horizontal distance from the plant. However, the roots in one particular soil horizon were the exception, for example roots at 40-50 cm soil layer in 70 DAS of perpendicular distance; root dry weights in this soil horizon were more than those in next upper (perpendicular distribution) or next farther (horizontal distribution) soil layer (Figure 4 and Table 6). The reason for this phenomenon might be that the soil conditions, such as water, nutrients, and temperature, in this soil horizon were more favorable for root growth (Zhang, 2006). This exemplifies the plastic response of roots to the variable soil environment (Liedgens & Richner, 2001).

In most studies, the growth of root systems is considered in terms of total root length and total dry weight increase, with little attention paid to the developmental process (Sylvain, 1993). This lack of relevant experimental data hampers progress in modeling the root system architecture (Diggle, 1988). In our studies, maize roots were sampled at different DAS, allowing a dynamic description of the root system architecture. The study of horizontal and perpendicular distributions of maize roots used a self-designed root-box. The root box study allowed high reproducibility, as well as a physically and chemically uniform soil layer environment (Kono et al., 1987). The three-dimensional distribution of a root system can only be obtained in the field, even though the physical and chemical environments might be heterogeneous.

5. Conclusions

The numbers of axile root on the upper phytomers of maize grown in black soil were higher than those on lower phytomers. Angles of axile roots on lower phytomers were larger: the angles of roots from P2 to P5 were 81.51°, 56.9°, 69.33°, 56.06°, respectively. Angles on upper phytomers were smaller, with those on P6 to P10 being the smallest, (30.13° to 40.72°). Mean length, maximal length, and maximum rooting depth of axile root on each phytomer all increased with DAS. Mean length, maximal length, and maximum rooting depth of axile roots on lower phytomers were larger than those on upper phytomers. Root dry weight in each soil layer increased with DAS; there was a rapid increase during from 50 to 90 DAS. About 80 percent of root dry weight was in the soil above 40 cm. Over 78 % of root dry weight in total dry weight per plant was within 20 cm in the horizontal direction from the plant.

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Table 1. Some soil physical and chemical properties in the study site

Parameter	Organic matter (g/kg)	Total N (g/kg)	Total P (g/kg)	Total K (g/kg)	Avail. N (mg/kg)	Avail. P (mg/kg)	Avail. K (mg/kg)	pH (g/kg)
Mean	26.90	1.20	1.06	16.87	118.8	18.00	111.0	6.60

Table 2. Number of axile root at different DAS in field

	Root types								
	P2	P3	P4	P5	P6	P7	P8	P9	P10
25 DAS	3.84^{a}±0.41								
40 DAS	4.46^{a}±0.51	4.08^{a}±0.48	3.12^{b}±0.44						
50 DAS	4.53^{a}±0.58	4.23^{a}±0.53	3.31^{b}±0.41	4.12^{a}±0.53	3.99^{a}±0.62				
70 DAS	4.56^{a}±0.63	4.32^{a}±0.56	4.03^{a}±0.49	4.34^{a}±0.48	4.11^{a}±0.56	5.89^{a}±0.85	12.12^{a}±1.46	18.78^{a}±2.05	
90 DAS	4.58^{a}±0.59	4.32^{a}±0.54	4.12^{a}±0.54	4.32^{a}±0.51	4.16^{a}±0.52	6.26^{a}±0.77	12.98^{a}±1.25	20.50^{a}±3.54	21.36^{a}±3.51

Different letters indicate a significant difference at $p<0.05$ with Fisher's LSD test in the interior-group.

Table 3. Mean length and maximal length of axile root of different DAS in field

	Root types								
	P2	P3	P4	P5	P6	P7	P8	P9	P10
Mean length (m)									
25 DAS	0.03^{c}±0.004								
40 DAS	0.37^{d}±0.07	0.32^{c}±0.05	0.11^{c}±0.01						
50 DAS	1.15^{c}±0.15	0.56^{c}±0.08	1.34^{b}±0.02	0.54^{b}±0.04	0.23^{c}±0.02				
70 DAS	1.86^{a}±0.41	1.89^{b}±0.42	1.99^{ab}±0.46	1.97^{a}±0.53	1.28^{b}±0.13	0.84^{b}±0.07	0.51^{b}±0.04	0.22^{b}±0.03	
90 DAS	1.98^{a}±0.42	2.37^{a}±0.51	2.33^{a}±0.53	2.01^{a}±0.44	1.82^{a}±0.21	1.75^{a}±0.24	1.39^{a}±0.16	1.24^{a}±0.14	1.11^{a}±0.14
Maximal length (m)									
25 DAS	0.11^{d}±0.02								
40 DAS	0.74^{c}±0.06	0.51^{c}±0.05	0.15^{c}±0.02						
50 DAS	1.63^{b}±0. 10	1.00^{b}±0.09	0.91^{b}±0.04	1.17^{b}±0.12	0.29^{c}±0.02				
70 DAS	2.20^{a}±0.23	2.10^{a}±0.28	2.09^{b}±0.23	2.15^{a}±0.34	1.41^{b}±0.54	1.04^{b}±0.12	0.60^{b}±0.05	0.24^{b}±0.01	
90 DAS	2.64^{a}±0.03	2.92^{a}±0.23	2.50^{a}±0.21	2.22^{a}±0.21	2.13^{a}±0.24	1.80^{a}±0.21	1.58^{a}±0.19	1.37^{a}±0.29	1.22^{a}±0.14

Different letters indicate a significant difference at $p<0.05$ with Fisher's LSD test in the interior-group.

Table 4. Maximum rooting depth (m) of axile roots at different DAS in the field

	Root types								
	P2	P3	P4	P5	P6	P7	P8	P9	P10
25 DAS	0.09^{c}±0.008								
40 DAS	0.33^{d}±0.03	0.30^{d}±0.03	0.08^{d}±0.006						
50 DAS	0.91^{c}±0.08	0.82^{c}±0.07	0.83^{c}±0.08	0.80^{c}±0.07	0.22^{b}±0.02				
70 DAS	1.73^{b}±0.09	1.62^{b}±0.15	1.34^{b}±0.15	1.54^{b}±0.14	1.34^{a}±0.11	0.95^{b}±0.09	0.43^{b}±0.05	0.24^{b}±0.01	
90 DAS	2.02^{a}±0.18	2.12^{a}±0.18	1.98^{a}±0.20	1.91^{a}±0.20	1.36^{a}±0.13	1.41^{a}±0.15	1.01^{a}±0.09	0.98^{a}±0.01	1.27^{a}±0.12

Different letters indicate a significant difference at $p<0.05$ with Fisher's LSD test in the interior-group.

Table 5. Dynamics of root dry weight in different soil layers during different stages

	soil layer				
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	underneath 80 cm
25 DAS	1.112^{d}±0.016	0.041^{e}±0.005			
40 DAS	1.494^{d}±0.152	0.135^{d}±0.021			
50 DAS	10.546^{c}±1.248	1.982^{c}±0.128	0.255^{c}±0.021		
70 DAS	31.563^{b}±3.214	4.741^{b}±0.268	2.853^{b}±0.144	0.861^{b}±0.076	0.185^{b}±0.022
90 DAS	55.195^{a}±5.377	9.305^{a}±0.752	4.207^{a}±0.312	2.048^{a}±0.251	1.322^{a}±0.099

Different letters indicate a significant difference at $p<0.05$ with Fisher's LSD test in the interior-group.

Table 6. Distribution of root dry weight in horizontal directions at different stages (in root boxes)

	The percentage of dry weight in total dry weight per plant which different distances from plant (%)		
	0–20 cm	20–40 cm	40–60 cm
25 DAS	83.38^{a}	16.62^{b}	
40 DAS	81.10^{a}	18.90^{ab}	
50 DAS	78.16^{b}	21.84^{a}	
70 DAS	82.55^{a}	16.20^{b}	5.25^{a}
90 DAS	81.37^{a}	16.48^{b}	2.15^{b}

Different letters indicate a significant difference at $p<0.05$ with Fisher's LSD test in the interior-group.

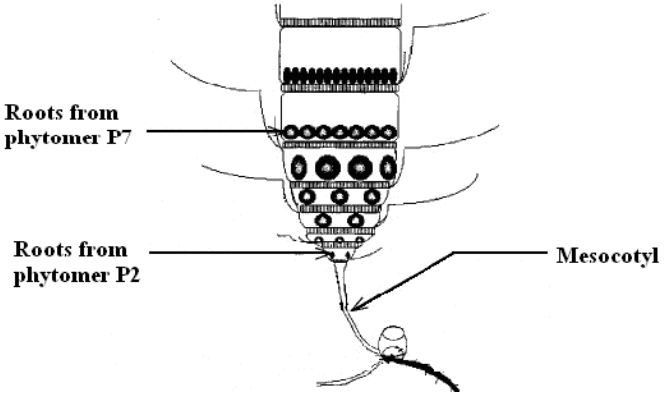

Figure 1. Structure of the bottom part of a maize plant and nomenclature used for the root system (adapted from Girardin et al. 1986)

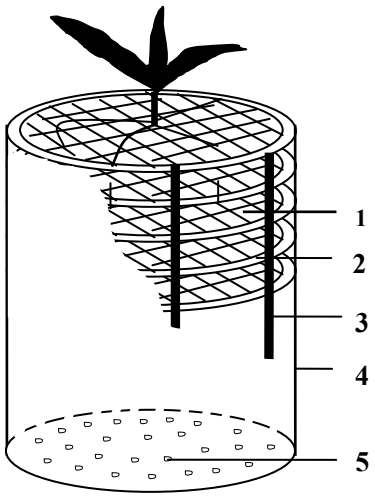

Figure 2. The design of the root box. 1, 2, 3, 4, and 5 mean mesh, network, post, sidewall and vents, respectively

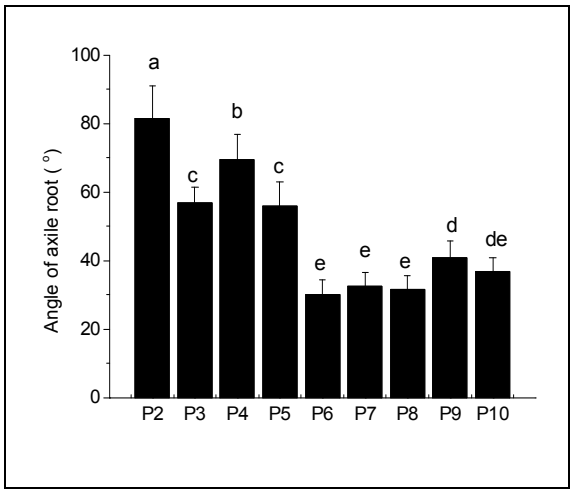

Figure 3. Angles of axile roots on different phytomers. Different letters indicate a significant difference at $p<0.05$ with Fisher's LSD test in the interior-group

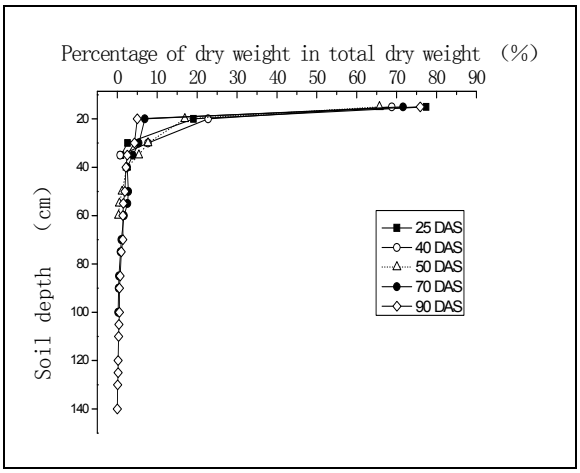

Figure 4. Distribution of maize root in vertical directions at different stages (in root boxes)

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