

Differences in size and architecture of the potato cultivars root system and their tolerance to drought stress

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ABSTRACT

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Drought can cause substantial yield losses, particularly for crops with shallow root systems, such as potato (*Solanum tuberosum*). This study tested whether root system architecture could affect potato yield under drought conditions. The following parameters of the roots were measured: depth range, total length, total area, surface area, average diameter, and total dry weight of the root system. These parameters in soil layers were also measured at different depths. Five potato cultivars from a group of mid-early cultivars were examined in this study. The same cultivars were tested under two conditions: control with optimal irrigation and drought stress treatment without irrigation for three weeks after the end of tuberization to check the tuber yield. Significant differences were observed among cultivars in the size of the root system and its architecture. The biggest differences in the individual layers of soil profile related to the diameter of the root, the root length, and the surface area. Also a relationship between the size of the root system and yield of tubers was found. The strongest correlations involved the root length and the root surface area with the decrease in tuber yield under the drought, then the dry root mass with the decrease in yield. These correlations were negative: the higher the value of the parameter, the smaller the observed decrease in yield. This showed a relationship between root length and mass with the decrease of yield; this relationship was stronger for roots in deeper layers than in the shallowest layers. Therefore, this study indicates that breeding potato cultivars with deep root systems might improve tuber yields under drought conditions.

Keywords: stress tolerance; tuber crops; water; nutrient; rainfall

The plant root system takes up water and dissolved nutrients from the soil; therefore the size and extent of the root system have important implications for plant development, yield, and survival under stress conditions. Potato plants (*Solanum tuberosum*) have relatively shallow root systems and, consequently, potato growth and yield depend on regular rainfall and are sensitive to water shortages (Wisconsin University 2002, Iwama 2008, Joshi et al. 2016).

Cultivars with larger and more expansive root systems are more likely to be able to retrieve water and nutrients from the soil. Therefore, these cultivars should be less susceptible to periodic droughts

(Głuska 2004, Wishart et al. 2013, Villardon et al. 2014) and more suitable for growing in production systems that use fewer inputs (water and fertilizer).

Measurement of the size and extent of the root system of different cultivars gives key information for breeding cultivars adapted to regions with frequent shortages of rainfall. Such cultivars may also be better suited to organic production and other low-input cropping systems. Information about the size of the root system can also provide important information for breeders. A research from the Iwama group (1998, 1999, 2008) indicates that breeding can select for the size of the root system and Japanese breeding

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programs have used root system architecture as a trait for selection (Iwama 1999, 2008, Kashiwagi et al. 2000). For example, the cv. Konyu was bred using the size of the root mass in the arable layer and tuber yield as selection criteria. Indeed, cv. Konyu plants show a significantly less-severe response to water shortages in the soil, compared with commercial cultivars (Iwama 2008).

Measurements of root system parameters require difficult and time-consuming labour (Smith et al. 1994, Tracy et al. 2011, Silberbush 2013, Khan et al. 2016). Therefore, most studies examine only a small part of the total plant material and comprehensive studies await improved methods for phenotyping. Several centres have carried out studies on the root system in a wide range of potato cultivars.

The research presented here is a continuation of work conducted in Poland.

In the current study, the variability of root system size and architecture was evaluated in several potato cultivars and looked for correlations between root system parameters and the tolerance of these cultivars to soil drought.

MATERIAL AND METHODS

The study was conducted in the years 2014–2015 in specially constructed cylindrical pots with open bottoms. Pots were made of sheets of galvanized steel with a thickness of 0.8 mm and were 1 m tall and 40 cm wide, allowing for proper development of the above-ground and below-ground parts of the plants. These pots can be opened along the seam of the cylinder, allowing the extraction of the entire root system, without damage (Głuska 1996).

Pots were filled with light, loamy soil brought from the field where potatoes are grown and mixed with sand in a ratio of 1:1. Every 20 cm, a metal net with a mesh size of approx. 0.5 cm was placed dividing the pot into 5 horizontal layers 20 cm thick. Seed potato tubers were placed approximately 5 cm below the upper surface of the soil. The roots of the growing plants pass into the soil profile and the mesh discs do not impede the growth of roots.

During the growing season the plants were fed twice. The root systems were measured when the plants were in full vegetation (blooming), in the third week of June, as the previous study found that potato plants show the largest differences in the size of the root system (Iwama 2008).

After being removed from the pots, the roots were washed and cut along the mesh grids, thus producing five portions from each plant for measurements. The following measurements were made: the depth range (cm), the total length of roots (m), the length of the roots of the individual layers (m), the total area of roots (m²), the surface area of the roots in the individual layers (m²), the average diameter of roots (mm), the diameter of the roots of the individual layers (mm), the total dry weight of the root system (g), and the dry weight of the roots in the individual layers (g).

The length, diameter, and surface area of the roots were measured using the Epson Expression scanner (Seiko Epson Corp., Japan) and the 10000XL WinRhizo software (Regent Instruments, Canada).

Five potato cultivars from the group of mid-early cultivars (Bogatka, Cekin, Gawin, Satina, and Tajfun), for which prior observations of the response to water scarcity are available, were tested and each cultivar was tested in 3 replications.

For the same cultivars, a pot experiment was conducted in the greenhouse. Two conditions were applied: control with optimal irrigation and a drought stress treatment with reduced irrigation for three weeks after the end of tuberization. After the end of the growing season, tuber yield (kg) was measured.

Statistical analysis of results was performed by an analysis of variance and regression using the Statistica software (StatSoft, Poland). The significance of the sources of variation was tested by the Fisher-Snedecor test. The significance of differences was assessed by the Tukey's test.

RESULTS

The potato cultivars showed differences in the root system size. The tested cultivars showed significant differences in all tested parameters, including the length, area, diameter, and dry weight of roots (Table 1).

The total length of the roots per plant ranged from 803.5 m in cv. Satina to 1399 m in cv. Gawin. Statistical analysis divided the cultivars into four groups with varying total lengths of roots (Figure 1a). The total area of the roots ranged from 79.5 m² in cv. Satina to 140.8 m² in cv. Gawin. The surface of the root system increases with its length, but division of cultivars into homogeneous groups

Table 1. Variation in the whole root system

Source of variation	Parameter	<i>P</i>	Mean
Cultivar	total length of roots (m)	0.002	1038.9
	total area of roots (m ²)	< 0.0001	99.5
	average diameter of roots (mm)	< 0.0001	0.303
	total dry weight of the root system (g)	< 0.0001	6.72

P < 0.05 was considered statistically significant

was somewhat different for root area, as statistical analysis distinguished two groups of cultivars with different root system areas (Figure 1b). The average diameter of the roots ranged from 0.274 mm in cv. Bogatka to 0.319 mm in cv. Gawin. Statistical analysis divided the cultivars into four groups based on root diameter (Figure 1c). The dry weight of the roots ranged from 5.06 g in cv. Cekin to 8.56 g in cv. Gawin and the division into groups based on dry weight is shown in Figure 1d.

Differentiation of the architecture of the root system. The cultivars differed significantly in terms of root architecture and in the distribution of roots in individual layers. The biggest differences

related to the diameter of the root, the smallest length and the root area (Table 2).

Rooting depth of all tested cultivars ranged up to 100 cm, but in the last layer (80–100 cm), the length and mass of roots were very small.

On average, the cultivars had the greatest length of roots in the second and third layer (at a depth of 20 to 60 cm) (Figure 2a). The root length in these layers was more than half the size of the entire root system. The fourth and the first layers had more roots than the bottom layer, but less than the second and third layers. Cultivars differed only in the first two layers; the other layers showed no significant differences (Table 2).

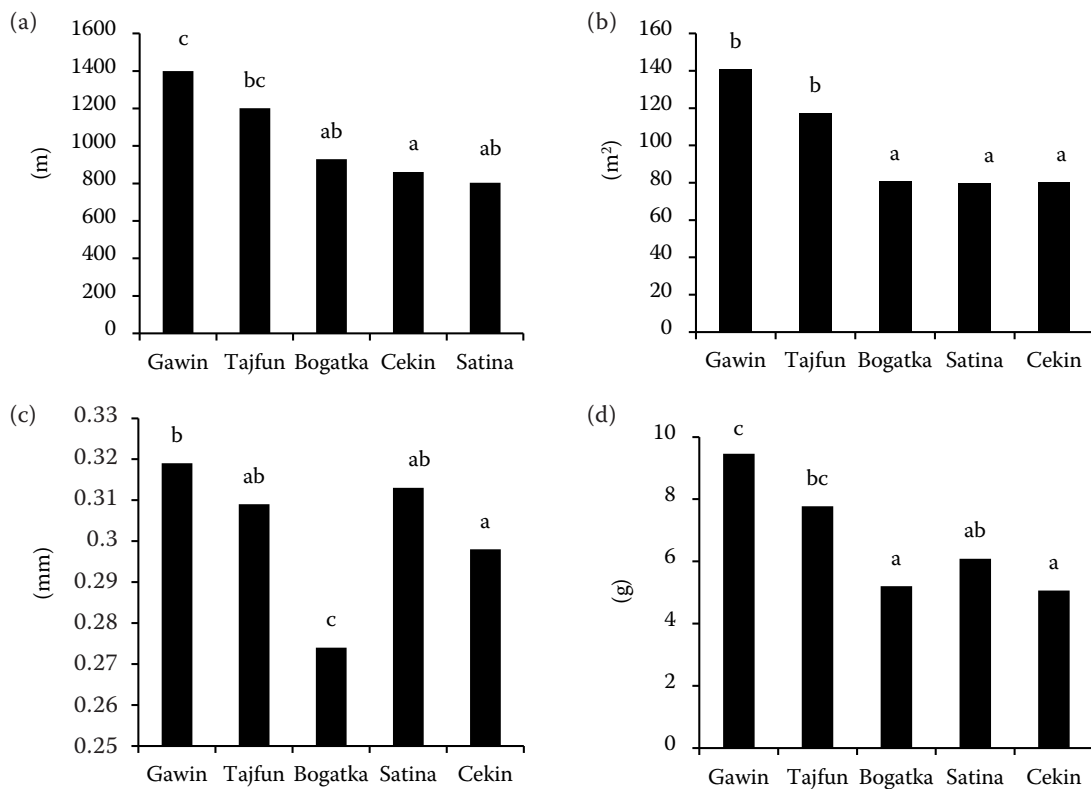


Figure 1. (a) The length; (b) the surface; (c) the diameter, and (d) the dry weight of the root system depending on the cultivar. ^{a,b,c}Mean values indicated by the same letters are not statistically significant at the 0.05 level by Tukey's test

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Table 2. Variation in the root systems of different cultivars in the soil profile

Tested parameter	Layer I		Layer II		Layer III		Layer IV		Layer V	
	<i>P</i>	mean	<i>P</i>	mean	<i>P</i>	mean	<i>P</i>	mean	<i>P</i>	mean
Root length (m)	< 0.0001	158.2	<0.014	288.9	0.009	285.9	0.077	228.0	0.043	77.6
Root area (m ²)	< 0.0001	16.7	< 0.014	16.7	0.018	27.0	0.040	20.7	0.25	6.9
Root diameter (mm)	0.013	0.341	0.033	0.308	0.005	0.300	0.022	0.288	0.002	0.276
Root mass (g)	< 0.001	1.88	0.010	1.84	0.095	1.56	0.050	1.09	1.09	0.34

P < 0.05 was considered statistically significant

The surface area of roots in the individual layers of the soil profile corresponded to the length of the roots. Changes in the value of this parameter also coincided with the differences observed for the length of the root system. For most cultivars, the largest root surface area was recorded in the second and third soil layer (Figure 2b). Differentiation among the cultivars was observed for the first three layers, but not in the other layers (Table 2).

The diameter of the roots of all cultivars decreased with increasing depth in the soil profile (Figure 2c). In the first layer (to a depth of 20 cm), the mean root diameter was 20% greater than that of the last layer (80–100 cm). The cultivars showed significant differences in all layers (Table 2).

Like the root diameter, the dry weight of roots also decreased in the soil profile (Figure 2d), however, this parameter showed a much larger decrease. Root mass in the first layer was about 83% higher than in the last layer. In the first two layers, the dry weight of roots exceeded 50% of the total root mass. There were significant differences among the cultivars in all five layers.

The relationship between root system size and architecture and the yield of tubers. The yield of tubers decreased to varying degrees when different cultivars were subjected to drought stress. The smallest decrease was observed in yield in cv. Gawin, and the largest decrease in cv. Cekin (Table 3).

Using the data on the size of the root system, the dependencies between root system parameters

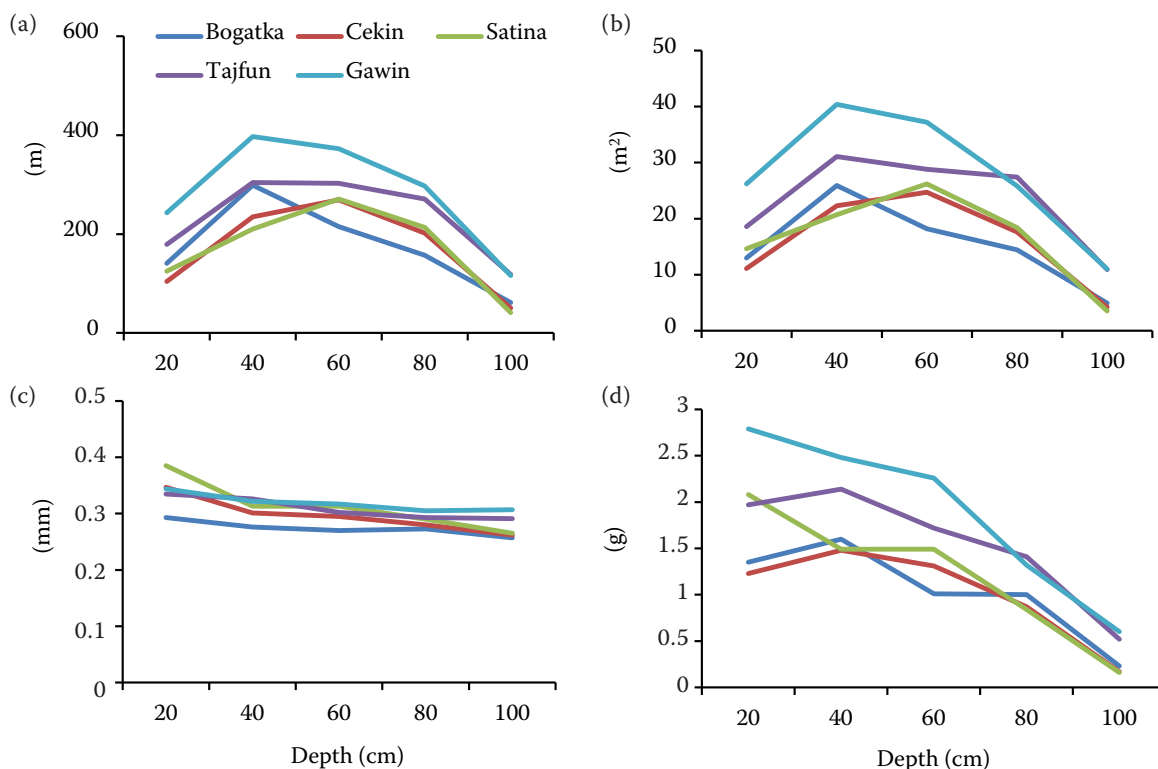


Figure 2. Varietal differences in (a) the length; (b) the area; (c) the diameter; (d) dry weight of the root system in the soil profile

Table 3. Tuber yield from 1 plant (g) in control and drought combination and a decrease in yield (%)

Cultivar	Control	Drought	Decrease (%)
Gawin	1155	950	17.7
Tajfun	1372	1125	18.0
Bogatka	1455	1025	29.5
Satina	1292	870	32.6
Cekin	1330	817	38.6

and yield were calculated (without drought, with drought, and the decrease in yield as a result of the applied drought). The strongest correlations involved the root length and surface area and the decrease in yield; the next-strongest correlations involved the dry root mass and the decrease in yield. Negative correlations were observed; that is, the higher the value of the tested parameters, the smaller the observed decrease in yield.

Weaker correlations involved the size of the root system and the yield of tubers after the drought treatment. There was a positive correlation for root system size and higher yield, but it was not statistically significant.

The weakest correlations involved the size of the root system and yield of tubers without drought. This paper further describes only the significant relationships.

The calculated coefficients of correlation between the length and dry weight of roots in the individual layers and the decrease of yield due to drought showed the greatest correlation between the parameters in the fourth layer; that is, the greater the length and weight of roots in the deeper layer (60–80 cm), the smaller the decrease in yield (Table 4).

Table 4. Correlation coefficients between the length and dry mass of roots in the individual layers and the decrease in tuber yield under drought

Root length	Correlation coefficient with yield decrease	Dry mass of roots	Correlation coefficient with yield decrease
Layer I	0.552	layer I	0.370
Layer II	0.470	layer II	0.516
Layer III	0.574	layer III	0.478
Layer IV	0.702	layer IV	0.600
Layer V	0.618	layer V	0.532

DISCUSSION

Under global climate change, drought tolerance will likely become increasingly important for producing stable yields in all crops (Hijmans 2003, Comas et al. 2013). Since current potato cultivars have low tolerance to drought, the enhancement of drought tolerance is an urgent task for potato researchers in the 21st century. Breeding of new cultivars with excellent root characteristics to absorb water from deeper regions of the soil and under lower soil water potential will increase the usage of soil water and contribute to efficient utilization of water from precipitation or irrigation in potato production.

Several studies have shown that potato cultivars differ in the size of the entire root mass and distribution of the roots of the individual layers of the soil (Opena and Porter 1999, Stalham and Allen 2001, Battiliani et al. 2008, Joshi et al. 2016). Roots are concentrated mostly in the plowed layer, up to 30 cm deep, and even under the mother tubers. Other studies showed a greater range in depth of roots. For example, Rykaczewska et al. (2015) found the maximum depth of rooting was 109 cm for mini-tubers and Głuska (2004) found that the depth of rooting ranged from 105–126 cm for regular seed potatoes. In our study, the depth of rooting of all cultivars was 100 cm (at the depth of the pots).

The total length of the roots per plant showed larger differences in different cultivars. Wishart et al. (2013) showed that root length of 28 genotypes ranged from 40–112 m per plant. In our study, this parameter ranged from 800–1400 m. The total root length has been shown to vary greatly in different cultivars, with differences in the length of the root system of more than 40%. The surface area of the root system varied similarly and cultivars differed in the diameter and the dry weight of the roots. In our study, the dry weight of roots was 5.06–8.56 g. Lahlou and Ledent (2005) found that root dry weight ranged from 1.1–11.8 g. Głuska (2004) and Rykaczewska (2015) obtained similar results.

Our study also confirmed the varied distribution of roots in different soil layers and confirmed the common presumption that most of the root mass of potato occurs at a depth of 50–60 cm. Indeed, for the five tested cultivars, more than 50% of the roots (by weight) were in the first and the second layer at a depth of 20–40 cm, and 23% of the roots were in the third layer at 60–80 cm deep. The largest root length (over 50%) was found in the second and third

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layers (40–80 cm) and about 22% was found in the fourth layer (60–80 cm). The smallest root length was found in the first and fifth layers. The root surface area showed the same distribution.

Many studies found a positive relationship between the size of the root system and the amount of above-ground biomass (Iwama 2008, Rykaczewska 2015). In our research a dependence was also observed, but these correlations were not statistically significant.

More interesting correlations involved the size of the root system and the tuber yield. In our study no significant correlation was found between the size of the root system and yield of tubers in the absence of drought treatment. Also a stronger (but not always significant) correlation was observed with the yield of tubers from the drought-treated conditions. A good correlation was found with the decrease in yield between the control and drought treatments. This was, of course, an inverse relationship: the larger the root system, the smaller drop in yield.

Attempts to find a correlation between the size of the root system and the size of the crop have been undertaken by many researchers (but not all managed to identify simple relationships. In a review of research on the root system of potato, Iwama (2008) states that the mass of roots generally indicates a positive correlation with the yield of tubers. Also Rykaczewska (2015) found that the drought-resistant cv. Tetyda was characterized by the greatest root system mass of the 17 tested cultivars. In our work, this observation was extended trying to find whether the distribution of roots in the soil profile is correlated with the response of potato plants to soil drought. Our analysis showed a greater correlation between the length and weight of roots in the deeper layers than in the shallowest layer. It can be concluded that the plants that have a more-developed root system at greater depths of the soil profile tend to have milder reactions to drought.

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