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Improved wheat grain yield by a new method of root selection

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Abstract Wheat is a major source of protein for human food, a critical issue at a time when mankind is growing by 77 million people per year. Wheat was domesticated approximately 10,000 years ago and has been systematically bred for about 200 years. However, this breeding selection has been done using only aerial plant parts. Indeed, wheat roots, the hidden half of plant, were not considered in breeding programs due to the lack of an appropriate method. Here, we evaluated roots of 18 wheat populations. The root system size was measured by its electrical capacitance directly in field. The plants in third and fourth generations were evaluated during shooting and heading. Then plants were selected for large and small root system. In dry conditions, progeny of plants with large and small root system had yields of 17.1 and 10.9 g per plant in the third generation and 18.5 and 10.0 g per plant in the fourth generation. Our results show that the progeny of the plants selected for large roots have larger roots than their parents, also in next generation. Similarly, the progeny of small root plants have smaller roots. The selection process showed a greater response for larger root system size. This response can be evolutionarily advantageous and make selection easier than, for example, selection for grain yield. Our unique method enables accurate, repeated evaluation and harvest of selected plants. Selection for higher wheat root system size can be easily used to breed for drought tolerance and higher efficiency of water and fertilizer use.

Keywords Winter wheat · Selection response · Root system size · Electrical capacitance · Drought tolerance

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1 Introduction

According to the United Nations, the world population exceeded the 7 billion in 2011 and it is currently growing by approximately 77 million people per year. Globally, wheat is the leading source of vegetable protein in human food. The annual production gain will need to reach near 2.5 % by the year 2025 to keep abreast of population growth (Curtis et al. 2002). Plant protein is cheaper with lower consumption of water and energy in comparison with animal protein. However, the current and projected relative progress rates in yield enhancement, under potentially low water conditions, are a topic of considerable concern. Yields are expected to be insufficient to meet the projected demand for cereals by 2050 (Hall and Richards 2013). The low yield capacity of contemporary farming systems is a major obstacle to the future growth of sustainable agriculture (e.g., Fasoula and Tokatlidis 2012). The availability of nitrogen is largely determined by root densities, and mineral fluxes are generally reduced under conditions of water deficit (Gonzalez-Dugo et al. 2010). The grain yield of winter wheat varieties in dry years is generally positively correlated with root system size, but this correlation is negative in certain environments. In a dry year, the varieties that showed the greatest difference in root system size were found to exhibit a yield difference of $860 \text{ kg} \cdot \text{ha}^{-1}$, approximately translating to an additional use of 15 mm of subsoil water (Středa et al. 2012).

Cereals are shallow-rooting plants. In experiments by Bodner et al. (2010), root density in a shallow layer was 4.6, 6.3, and $8.6 \text{ cm} \cdot \text{cm}^{-3}$ for vetch, mustard, and rye, respectively. A significant positive correlation was found between root biomass and P and K uptake. Wheat genotypes with superior root characteristics for efficient nutrient uptake, especially during tillering and booting stages, should be developed in breeding programs to increase grain yield and to minimize nitrate leaching (Ehdaie et al. 2010).

Crossing early green-revolution wheat to an F_2 of Norin 10 or Brevor reduced root biomass. Later-generation semi-dwarf wheat showed genetic variation for root biomass, but some generations exhibited a further reduction in root size (Waines and Ehdaie 2007). These results support our research and suggest practical breeding methods.

We proposed that roots should be evaluated during the shooting and heading stages, times when nutrient requirements are the highest because of the rapid increase in biomass. Furthermore, the selected plants should be harvested for reproduction and used to develop new varieties. We previously developed and applied an electrical capacitance method to evaluate the size of the intact root system in the soil (Chloupek 1972). The aim of our research was to repeatedly evaluate wheat root system size during practical field selection and to determine its effect on grain yield.

1.1 Evaluation of root system size in soil by measuring its electrical capacitance

1.1.1 Theory

During its passage through a substance, alternating electric current encounters an impedance barrier consisting of ohmic resistance, capacitance, and inductance. While inductance is not present in plant tissues, resistance and capacitance are separate, but parallel impedance factors. Therefore, plant tissue shows parallel capacitance, and its electrical capacity is measured in micro and nanofarads. The greater the mutual area of the capacitor plates, the smaller their mutual distance, and the higher the permittivity (dielectric constant) of the dielectric between the plates, the greater the capacitance. Water, paper (cellulose), and air gaps have very different permittivities, with relative values of 80, 3, and 1, respectively. The permittivity of cellulose increases with its water content and depends on the frequency (kHz) at which the capacitance is measured (e.g., Guegan and Foulc 2009). Over a range of 7–1,000 Hz, the ratio of the capacitive to resistive components of tissue impedance in excised muscle was greatest at 1 kHz (Schwan and Kay 1957). Therefore, we used 1 kHz in our study. Lipid bilayers, the basic structural elements of cell membranes, are the basis for many of the properties of these membranes. The formation of the membrane is indicated by an increase in its electrical capacity. The approximate value of electrical capacity for biological membranes is $0.9 \mu\text{F} \cdot \text{cm}^{-2}$ (Montal and Mueller 1972). This uniform, specific electric capacity of biological membranes per unit area inspired Chloupek (1972) to evaluate the relationship between root system size and electrical capacitance. Roots and other plant tissues have been found to respond in a manner similar to that of cylindrical conductors and parallel-plate capacitors at a frequency of 1 kHz. Notably, the age of the plants has been

found to have little effect on the dielectric properties of maize tissues (Walker 1965).

These data show that the measured capacitance reflects not only root size but also membrane vitality, as dying membranes lose capacitance.

1.1.2 Application

Chloupek (1972) evaluated the correlation between root system size (fresh and dry weight, and volume and surface area) and electrical capacity (C) in maize, sunflower, oat, and onion. The measurements of electrical capacity were performed in the soil in which the plants grew. The highest correlation was found for parallel capacitance at 1 kHz. Dvořák et al. (1981) and Zhang et al. (1995) demonstrated a positive relationship between the area of plant membranes and their electrical capacity in a plant-soil system. In measurements of electrical capacity, Dalton (1995) suggested that roots form columnar capacitors, the epidermis forms external electrodes, and the xylem forms internal electrodes that are analogous to the plates of a capacitor. Dying and dead yeast cells showed low capacitance (Patel et al. 2008).

More studies, cited by Chloupek et al. (2010), report a significant correlation between root size and its capacitance. Recently, Cseresnyés et al. (2012) reported the correlation between electric capacitance and root dry mass ($R^2=0.937$) and root surface area ($R^2=0.893$) in maize. Ellis et al. (2013) reported the following important findings: (i) the root system was the primary constituent of the measurements and (ii) the root system acted as the capacitor. The relationship between the electrical capacitance and the area of the stem bases was weak. They found that the evaluation of electrical capacitance is a rapid and nondestructive method of root size evaluation because the capacitance was significantly correlated with root mass, length, and surface area. However, the predictive power of electrical capacity in this scenario was poor. The entire root system contributed to the measured electrical capacity, and the measured permittivity dictated the value found in the plant tissue. These results supported Dalton's model, where the measured electrical capacity was a parameter of the root system.

The isolation of intact living root systems from the soil in the field has not yet been performed and appears to be impossible (Fig. 1). We are unaware of any method suitable for the repeated evaluation of root system size in the same plant at different developmental stages or the evaluation of many plants in segregated populations, an important prerequisite for successful practical breeding. The selected plants must be able to produce seeds for evaluation and reproduction in subsequent generations. These requirements were satisfied by the method used in this study. Repeated evaluations decreased the inaccuracy of the method. Ellis et al. (2013) reported errors in the range of 69–79 %. Using the average of two or three

Fig. 1 Electrical capacitance of root system measured in relation to the surrounding soil includes also root hairs which cannot be evaluated by excavating from the soil (roots of wheat; *enlarged*)

measurements taken during the vegetative period would decrease this error range to 48–62 % (69^2 – 79^2) and 23–38 % (48^2 – 62^2), respectively. Because breeders evaluate selected progeny in multiple generations, the resulting lines may have a significantly greater root system size.

2 Materials and methods

2.1 Plant selection

Six varieties (*Akteur*, *Meritto*, *Sakura*, *Simila*, *Sulamit*, and *Vlasta*) were mutually crossed at the Plant Breeding Station Úhřetice in the Czech Republic in the Central Europe in 2008. The resulting 18 populations were sown in the field on October 13, 2008, and harvested as F_1 generation on July 29, 2009. In 2009, the F_2 generation was sown at three stations, Úhřetice (UTM coordinates 33 N 561,956 mE 5,535,514 mN, altitude 235–258 m.a.s.l., medium loamy degraded chernozem soil—according to IUSS Working Group WRB 2007 classification), Chlumec nad Cidlinou (Chlumec; UTM coordinates 33 N 534,999 mE 5,554,784 mN, altitude 235–254 m.a.s.l., medium and light loamy and loamy-sand haplic luvisol soil), and Hustopeče (UTM coordinates 33 N 626,018 mE 5,419,581 mN, altitude 183–246 m.a.s.l., light loamy-sand chernozem soil). Root system size was not evaluated in 2010 due to rainy weather, particularly in April and May. The F_2 generation was harvested only in Úhřetice on August 13, 2010. The F_3 generation was sown on October 12, 14, and 8, 2010, at Úhřetice, Chlumec, and Hustopeče, respectively. In 2011, the root system size was measured in shooting plants on May 11 and 12, and in heading plants on June 3, May 31, and June 5. The plants were harvested on August 15, 12, and 11, 2011, at Úhřetice, Chlumec, and Hustopeče, respectively. For each combination, the plants were separated into A and B selection groups and, with their parents, were sown in the F_4 generation at Úhřetice, Chlumec, and Hustopeče on October 18 and 17 and September 28, 2011, respectively. According to data obtained from the nearest climatological station, the Czech

Hydrometeorological Institute, located up to 5 km away, there was poor emergence caused by heavy drought (Table 1). As a result, the experiments in Úhřetice and Hustopeče were not evaluated. Only the selected progeny in Chlumec were evaluated. Root system size was measured in shooting plants on May 24, 2012, and in heading plants on June 7, 2012. The crop was harvested on August 13, 2012.

Field experiments through the F_4 generation were randomly sown by hand in four replicates, with parents in rows consisting of ten plants, spaced at 0.10×0.15 m. During the shooting and heading stages, the root system size was measured in six of the inner plants only. From each replicate of the 18 populations, the two plants with the largest (A) and the two with the smallest (B) roots were selected. Seeds from eight plants from each of the A and B selection groups (four replicates $\times$ two plants) from each of the 18 combinations were bulked and sown similarly in the following generation.

In the F_5 generation, the single best A selection plant of each combination was grown in 0.36-m^2 plots (three rows 0.80 m in distance 0.15 m). This regular spacing was used because root system size cannot be evaluated if a canopy is present.

All trials were managed according to standard agronomic practices. Nitrogen fertilization varied from 75 to $100\text{ kg}\cdot\text{ha}^{-1}$. Pesticides were used as needed to control weeds and insects. Herbicide was typically applied in April or May (two applications in Úhřetice 2012/2013). Insecticide was applied from zero to three times (typically once). Fungicide treatments were not applied.

2.2 Capacitance measurements

The root system size was measured in nanofarads (nF). One wire of the capacitance meter was connected using a clamp to all the basal parts of the plant of equal height. This height was near the soil but not in contact with it. The second wire, which leads the measuring current to the soil, was grounded in the spacing, midway between the measured plants. An impedance bridge ESCORT ELC-131D LCR meter (Escort Instruments

Table 1 The meteorological conditions during the experimental years. The average annual (January to December) air temperature (°C), annual rainfall total (mm), and seasonal (March to July) soil moisture, expressed as the percentage of seasonal available soil–water holding capacity are

Location	Average annual temperature			Average annual rainfall			Seasonal available soil–water holding capacity (%)		
	2011	2012	2013	2011	2012	2013	2011	2012	2013
Hustopeče	10.0	10.2	9.7	429	511	528	44	39	56
Úhřetice	10.0	9.8	9.2	560	636	587	45	47	89
Chlumec	10.2	9.9	9.5	556	689	560	38	32	94

Corporation, Taiwan) was used and set to parallel measured capacitance at a frequency of 1 kHz.

2.3 Evaluation of heritability

Heritability (h^2) is the percentage of trait variation inherited into progeny. In relation to the parents in the same year, the realized heritability in the root system size in our experiment was calculated from the selection difference in the parental generation (S) and realized difference in progeny (R): $R=h^2 \cdot S$ (e.g., Falconer 1989). Heritability can also be estimated using the coefficient of determination, the square of the linear correlation coefficient calculated between generations. The realized heritability has a higher relevance for practical breeding.

2.4 Statistical analysis

Results of the root system size and grain yield were evaluated using a multifactor analysis of variance and a correlation analysis using STATISTICA statistical software (StatSoft, ver. 7.0, Tulsa, OK, USA). Significant values ($P<0.05$) are marked with an asterisk (*) and highly significant values ($P<0.01$) are marked with a double asterisk (**).

The reliability of our root measurements was compared to that of grain yield measurements using the percentage of the experimental error (unexplained variation) of the whole variation, calculated from standard deviations (root of mean squares in analysis of variance).

3 Results and discussion

3.1 Root system size and crops

Dietrich et al. (2013) showed that root size could not be evaluated using electrical capacitance because it is strongly influenced by soil moisture. Our data support this statement. In the F_3 generation (harvested in 2011), the root system size of all parental varieties was averaged at 3.75 nF. The grain yield of the A and B selection groups was 17.10 and 10.90 g per plant, respectively. However, as shown in Table 2, the root

system size was 6.41 nF in the F_4 generation (harvested in 2012), with a grain yield of 18.47 and 9.99 g per plant for A and B selections, respectively. The soil moisture analysis showed that the root system size of the F_3 generation, at all three stations, was evaluated under moisture-stressed conditions. The amount of seasonal available soil–water holding capacity in shooting and heading stage plants was as follows: 28 and 9 % in Úhřetice, 41 and 9 % in Hustopeče, and 9 and 4 % in Chlumec. The root system size of the F_4 generation in Chlumec was evaluated under different soil moisture conditions, 6 and 11 % in shooting and heading plants, respectively. Even if the soil conditions were different in the different years, both the grain yield and root system size measured by electrical capacitance could be reliably compared among the populations produced in the same year.

Walker (1965) found that the root tissue of *Zea mays* in Hoagland's solution acted like cylindrical conductors and parallel-plate capacitors at a frequency of 1 kHz, forming part of the electrical circuit. Therefore, it was unexpected that the capacitance measured was largely determined by the tissue between the surface of the substrate and the electrode attached to the plant (Dietrich et al. 2013), even though they reported a correlation between the electrical capacitance and root size ($R^2=0.70$, $n=67$) (Dietrich et al. 2012).

The reliability of our root system size measurements, as a combined percentage of experimental error in F_3 , F_4 , and F_3 and F_4 together in the analysis of variance, amounted to 2.9, 7.0, and 6.0 % for the root system size, and 5.6, 9.5, and 6.0 % for grain yield, respectively. Experimental factors we examined were population, selection, and generation (sum of standard deviations for the experimental factors accounted for the remainder of the variation to 100 %). Therefore, the reliability of both evaluations was similar. Our evaluation of three generations of winter wheat root size and grain yield is shown in Table 2.

The average root system size of 18 F_3 populations (2011) was 4.39 nF in A selections, 3.05 nF in B selections, and 3.75 nF in the parents. The average difference in comparison to the parents was +17.1 in A selections and –18.7 % in B selections. In the F_4 generation (2012), the average root system size in A selections was 6.88 nF, 6.23 nF in B selections, and 6.41 nF in the parents, an average difference of +7.3 and

Table 2 Average root system size (in nanofarads; nF) of 18 experimental winter wheat populations calculated from two measurements each year. Grain yield (g per plant in F₃ and F₄, and g per 0.36 m² in F₅) arecompared to the parents (F₃ in 2011, averaged from Chlumec, Úhřetice, and Hustopeče and F₄ in 2012 from Chlumec)

Nr.	Particular parents		F ₃ generation					F ₄ generation				F ₅ generation	
	Female	Male	A sel.	B sel.	Parents	Grain yield		A sel.	B sel.	Parents	Grain yield		A sel. grain yield
						A plants	B plants				A plants	B plants	
1	Akteur	Meritto	4.36	3.02	3.93	17.12	9.98	7.52	6.44	6.78	13.32	9.50	273
2	Akteur	Simila	4.71	3.49	3.89	17.43	10.95	7.09	6.07	6.77	20.08	7.15	273
3	Akteur	Sakura	4.56	3.18	3.92	18.29	10.71	7.04	7.07	6.44	19.47	15.43	259
4	Akteur	Sulamit	4.80	3.34	3.84	21.13	12.69	7.36	7.05	6.99	22.61	9.13	237
5	Meritto	Sulamit	4.18	2.88	3.55	17.41	11.92	7.25	5.78	6.05	23.33	11.40	274
6	Sakura	Meritto	4.27	2.67	3.73	17.39	9.09	7.14	5.85	5.50	18.98	11.43	211
7	Sakura	Simila	3.84	2.81	3.69	16.14	11.47	5.52	4.43	5.49	18.03	6.78	309
8	Sakura	Akteur	4.49	3.14	3.92	15.67	10.16	7.73	6.87	6.44	18.94	13.50	278
9	Sakura	Sulamit	4.79	3.13	3.64	19.36	12.28	6.32	5.08	5.71	18.49	8.35	267
10	Simila	Sulamit	4.06	2.95	3.60	17.38	10.45	5.40	5.13	6.04	15.90	7.30	330
11	Simila	Meritto	4.18	2.88	3.69	20.21	13.22	7.24	5.98	5.83	24.79	12.64	242
12	Sulamit	Sakura	3.68	2.61	3.64	12.07	9.85	6.61	6.94	5.71	17.38	12.13	206
13	Sulamit	Akteur	4.29	3.20	3.84	14.71	11.40	7.18	6.54	6.99	20.91	6.07	243
14	Vlasta	Sulamit	4.69	3.12	3.62	15.42	10.70	6.17	6.62	6.99	9.20	6.84	111
15	Vlasta	Meritto	4.66	3.32	3.71	17.07	10.65	7.60	7.00	6.78	18.57	8.55	216
16	Vlasta	Simila	4.22	2.87	3.67	17.00	10.34	5.68	5.86	6.77	15.84	11.17	231
17	Vlasta	Akteur	4.87	3.34	3.90	18.39	10.03	7.63	6.62	7.72	16.25	15.17	242
18	Vlasta	Sakura	4.34	3.03	3.70	15.53	10.34	7.29	6.03	6.44	20.37	7.26	176
	Average		4.39	3.05	3.75	17.10	10.90	6.88	6.23	6.41	18.47	9.99	243.2

−2.8 % for A and B selections, respectively, in comparison to the parents grown in the same year. Therefore, the progeny of plants selected for larger root system size had a larger root system size, and the progeny of plants selected for smaller root system size had a smaller root system size. The A selection resulted in an inherited increase in root system size of +7.3/+17.1=+0.43 in the following generation, whereas the corresponding result for the B selection was −2.8/−18.7=−0.15. It appears that the selection for larger root system size was more evolutionarily advantageous than that for small root system size. In a similar study using spring barley, Svačina et al. (2014) found that the response to A selection and B selection was +9.8 and −5.3 %, respectively. Here, the response to A selection in wheat was markedly higher (43 %) than that previously reported for spring barley. We attribute this difference to the selection of F₃ generation wheat at the three stations, decreased environmental variation, and increased genetic variation, making the selection more efficient.

Understanding the major limitations placed on root growth is extremely important if we are to maximize water and nutrient use and increase yields. These limitations may include insufficient rooting depth, root diseases, nutrient deficiencies, toxicities, and soil hardness (Richards 2008). Larger investment by the crop in fine roots deep in the soil and less

proliferation of roots in surface layers would improve yields by allowing the plant access to extra resources. The economic return on investment for water capture in roots has been found to be twice that of the same amount invested for nitrogen capture (King et al. 2003).

The root system size of parental varieties was significantly correlated with that of the F₃ progeny (A, B, and A+B progenies, $R^2=0.262^*$, 0.314^* , and 0.326^* , respectively). These coefficients of determination between close generations can be regarded as coefficients of heritability, the percentage of the genotype inherited by the progeny. The values obtained (0.26–0.33) are relatively high, but such high values are normal when a selection criterion is used for the first time.

Table 3 shows that under A selection, the Simila variety exhibited a decrease in root system size in both generations, whereas Akteur exhibited an increase in root system size. This difference was statistically significant. In our previous work (Sředa et al. 2012), we evaluated approximately 20 wheat varieties over 4 years, but only seven in all years. The Akteur variety showed the greatest root system size over the 4 years (2.67 nF, averaged from three measurements, compared to 2.23–2.52 nF in the other six varieties). Therefore, this variety was used in this study and we recommend its use when breeding for greater root system size.

Table 3 Average root system size (in nanofarads) of populations, for which a particular variety was used as one parent

Variety	F ₃ (2011)		F ₄ (2012)		Averaged
	Average of A populations	Average of B populations	Average of A populations	Average of B populations	
Akteur	4.58	3.24	7.36	6.67	5.46
Meritto	4.33	2.95	7.35	6.21	5.21
Sakura	4.28	2.94	6.81	6.14	5.04
Simila	4.20	3.00	6.19	5.49	4.72
Sulamit	4.36	3.03	6.61	6.27	5.07
Vlasta	4.56	3.14	6.87	6.43	5.25

3.2 Response to selection

The response to selection (R) is related to the selection difference in the parental generation (S) and the heritability of the trait (h^2), and is represented by the equation $R = h^2 \cdot S$ (e.g., Falconer 1989). We evaluated both the selection difference for root system size in relation to the parents and the response to selection similarly in the following generation. As shown above, the heritability was 0.43 (+7.3/+17.1=+0.43) under A selection and 0.15 (−2.8/−18.7=−0.15) under B selection. The heritability under A selection is similar to the heritability of root system size evaluated by electrical capacitance in maize (50 %) (Messmer et al. 2011) and is unexpectedly high, perhaps due to evolutionary advantage. Our values of the realized heritability are similar to those calculated from the coefficient of determination for the trait between successive generations (0.26–0.33).

3.3 Root system size and grain yield

Root system size was also evaluated in relation to grain yield in F₃, as shown in Fig. 2. The correlation was highly significant under A selection ($R^2=0.423^{**}$; $P<0.005$), but not under B selection ($R^2=0.139$).

Greater root system size needs not to be advantageous in all years for improved grain yield (Středa et al. 2012). Figure 2 shows that the plants under A selection had populations with large root system size and high yield, enabling selection for the trait. Of course, the correlation is not absolute. Of the variation in grain yield, 42 % (R^2) was explained by the root size. Root system size could not be evaluated in F₅ because evaluation required regularly spaced plants, not a stand. However, it is more reliable to determine yield in a stand than in spaced plants. The correlation between the yield of the F₃ and F₄ combinations was $R^2=0.140^*$ ($P<0.05$) and was $R^2=0.093$ between F₄ and F₅ in A selection plants. Therefore, 14 and 9 % of the yield increase caused by larger root system size was inherited into the F₄ and F₅ generations, respectively. This is normal in polytrait selection for characteristics controlled by many genes, such as grain yield and root system size

(Chloupek et al. 2006). The F₄ generation was sown from a bulk of selected plants, but F₅ was sown only from one. This could also decrease the inheritance.

Durum wheat showed a stronger response to water availability in fine roots and produced more fine roots in a moist year, and the electrical root capacitance was higher in *Khorasan* wheat (Ebrahimi et al. 2013). We found genetic differences at the variety level (Středa et al. 2012) and in segregating populations between progeny of the Akteur and Simila varieties. The strategy of increasing post-anthesis dry matter production through an enhancement of root activity during grain filling has been proposed as an approach to increase the grain yield of wheat in China (Li et al. 2012). One of our two measurements was performed near the time of grain filling. A large root system size contributes to increased capture of water and nitrogen early in the season (our first measurement) and facilitates the capture of additional water for grain filling. The usefulness of a vigorous root system in increasing wheat yields under water-limited conditions may

Fig. 2 Regression of grain yield on root system size for the plants under A selection, as averaged from three locations in 2011 (F₃). The scatter plot is shown with 95 % confidence ellipse. The confidence ellipse shows where a specified percentage of the data in a scatter plot will lie. Only 17 averages were evaluated because one progeny had an outlying average. Equation of the linear regression: $y = 0.2604 + 3.784x$

be greater in environments where crops rely largely on seasonal rainfall, such as Mediterranean-type environments (Palta et al. 2011).

As Central Europe experienced two dry years during the 5-year experimental period, approximately two fifth of the cereal varieties tested should have greater root system size, according to the results of our studies. Higher seed vigor, evaluated as the percentage of germination under drought and temperature stress, could also contribute to the goal of effective grain yield enhancement (Ullmannová et al. 2013).

We confirmed that selection, including that based on root system size evaluation, might contribute to the goal of increasing grain yield more effectively. These results are in agreement with the previously reported results for barley (Chloupek et al. 2010; Svačina et al. 2014) and wheat (Středa et al. 2012).

4 Conclusions

Our results showed that the progeny of the plants selected for large root size in the F_3 generation also had larger root system sizes than their parents in the next generation. Similarly, the progeny of plants selected for small root size also had a smaller root system size in the next generation than their parents. The root system size was correlated with grain yield in the F_3 generation. These results show an efficient selection for root system size and accompanying effects on grain yield. Such a selection was made possible by using electrical capacitance measurements. This promising selection method can be used to breed for drought tolerance and higher efficiency of water and fertilizer use.

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