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*Review*

# Field phenotyping of plant roots by electrical capacitance – a standardized methodological protocol for application in plant breeding: a Review**

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A b s t r a c t. Due to the absence of a suitable method and standardized procedures, the root systems of plants have been evaluated to a much lesser extent than aboveground organs. The aim of this article is (i) to provide a detailed description and thus standardization of an upgraded procedure of electrical capacitance measurement for evaluating the size of the root system of plants *in situ*, which allows for a reassessment to be made during the growing season and subsequent harvest of seeds for the planting of selected progenies, (ii) to demonstrate, through a standardized methodological protocol, the applicability of root electrical capacitance measurement as a field phenotyping method for the selection of superior root systems to improve crop abiotic stress tolerance and resource efficiency, (iii) to suggest a standardized methodological protocol for the application of electrical capacitance measurements in breeding nurseries, and (iv) to discuss the methodological aspects, development and limitations of this method. A methodological overview of the use of electrical capacitance to measure plant root systems, which emerged from working groups directed by the author of this unique method, is presented along with a standardized protocol. An overview of the application of electrical capacitance measurements of roots in breeding is shown along with some examples of successful applications.

K e y w o r d s: root system, drought tolerance, varieties, yield

## INTRODUCTION

The impact of most agricultural interventions (fertilization, irrigation, tillage) on crop growth and yield is mediated via the plant root system. Despite the essential role of the root system in determining attainable yields, roots have been historically overlooked as the hidden half of plants (Manske and Vlek, 2002; Waisel *et al.*, 1991) and rarely targeted by agricultural crop improvements. With a higher frequency of drought in the context of climate change, and considering that water limitation is a major yield-limiting factor that is increasingly prevalent in temperate regions, plant breeding efforts have started to search for approaches that integrate the root system into the stress tolerance portfolio for trait-based crop improvement. There are several lines of evidence, which show that targeting the root system in the breeding process is highly promising for improving yield stability and crop performance in stress inducing environments. Some biologists, physiologists and breeders involved in plant root research consider the root system to be the key to a second green revolution, which does not rely on expensive inputs (*e.g.*, Gewin, 2010).

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## Root systems for crop improvement – which trait to select for?

The measurement of root characteristics is made difficult by the environment in which the roots develop. In fact, the size of the roots has not been used as a criterion for selection in practical breeding efforts (with the exception of root crops – sugar beet, carrot, *etc.*), although every new selection criterion initially shows a prompt response to selection as a rule. A rare practical outcome of this was the cultivation of wheat with reduced hydraulic conductivity of the vessels of the root system xylem in Australia's arid climate (Richards and Passioura, 1989).

An important question is which characteristics should be selected by breeders to obtain drought-tolerant plants. Selecting a suitable variety (based on the root system properties) for a specific area may be the key to a grower's success. For example, deep-rooted varieties may be successful in dry years in soils with a higher water table. Gregory *et al.* (1978) found that only 3% of the total wheat root biomass occurred at a depth of 1 m, and this small portion provided up to 20% of the water needed for transpiration during the summer months. Kirkegaard *et al.* (2007) reported an increase in the grain yield of wheat by 59 kg $ha^{-1}$ per 1 mm of water delivered to a layer of 1.35-1.85 m during drought stress after flowering. Additionally, the topology of the root system, *e.g.*, the different branching angles of the seminal roots in wheat (Manschadi, 2006), is related to the water uptake efficiency.

A larger root system is considered to be an advantage, especially in the absence of sufficient water and nutrients, in a less fertile environment and in organic farming (Comas *et al.*, 2013; Svačina *et al.*, 2014), for enabling a more effective use of the nutrients from the soil, and thus lowering the contamination of the environment with unused nutrients, especially nitrogen and phosphorus (Gewin, 2010; Klimek-Kopyra and Rębilas, 2018). However, a higher root density did not always lead to an increase in nitrogen consumption (Wendling *et al.*, 2016; Feng *et al.*, 2016; Herrera *et al.*, 2010). When comparing old and modern wheat varieties, Aziz *et al.* (2017) discovered that the root length density and total length of the root system decreased with ongoing breeding processes, but the efficiency of nitrogen uptake increased. Genotypes with superior root characteristics for efficient nutrient uptake should be developed in breeding programmes to increase grain yield and to minimize nitrate leaching (Ehdaie *et al.*, 2010; Robinson *et al.*, 2018), and appropriate phenotypes must be precisely identified for intentional breeding. Despite improvements in molecular technologies, fast and accurate phenotyping remains the major bottleneck to enhancing yield gains in water-limited environments (Richards *et al.*, 2010).

However, the shallow topsoil profiles of stony soils are inappropriate for deep-rooted varieties. Blum (2005) considers plants with a deep reaching extensive root system to be ill suited for conditions of rapid drying of the upper layer of the soil, which (by its mechanical properties) prevents the pronounced proliferation of roots. Growth is then curtailed, so that the genetic potential for long roots remains unused.

In contrast, Richards (1991) stated that, for some environments, the formation of fewer roots in the upper soil layer may be an effective adaptation to drought. This could be related to the conclusions of Campos *et al.* (2004), who investigated the water obtained by the root system of old and modern varieties of maize. The old varieties showed a higher depletion of water predominantly from the upper parts of the soil profile. In particular, the depletion of water in the soil prior to the beginning of flowering was the reason for a more pronounced decline in the yield of older varieties compared to that of modern hybrids. The "Green Revolution" resulted in dwarf varieties of wheat capable of responding to higher fertilizer inputs, but they failed to reach resource-poor farmers. Crossing early green revolution wheat varieties, with an $F_2$ of Norin 10 or Brevor, reduced root biomass. Later generation, semi-dwarf wheat showed a genetic variation in root biomass, but some generations exhibited a further reduction in root size (Waines and Ehdaie, 2007). From this point of view, the optimal regionalization of varieties with a larger root system is essential.

Optimally, it is also desirable to take into account the root system morphology of a particular variety (the depth of the root system) or the dynamics of root growth during vegetative growth. Significant correlations between the root system size of barley in the stage of stem elongation during moderate drought stress and the seed vigour of progenies were found by Vintrlíková *et al.* (2015). It is likely that the increase in the root system of parents during drought stress conditions has enabled the rapid growth of the roots of progenies at the beginning of the vegetation period. However, a large sized root system is not always a great advantage. For example, if drought does not occur, then the development of a larger root system was an unnecessary investment for the plant at the expense of other photosynthetic products. The precise targeting of a variety to a particular area of cultivation may serve as the basis for the success and economic prosperity of farmers.

For an improved exploitation of the available water, an adequate distribution of roots in the soil profile is preferable to a higher dry matter content of the roots (Bänziger *et al.*, 2000). In cereals, root densities of 1.0-1.5 cm $cm^{-3}$ are required for the plant to extract the available water from the soil (Passioura, 1980; Vamerali *et al.*, 2003). Lynch (2013) characterized the maize ideotype for its optimal uptake of water and mobile nutrients as steep, cheap and deep. This promotes the phenotypic or genotypic selection of a larger (deeper) root system in cereals.

Fitter (2002) reported that high values of SRL (specific root length; root length per root weight unit) indicates the high ability of the roots to obtain nutrients. Similarly, Gonzalez-Dugo (2010) reported that the availability of nitrogen is largely determined by root density. Palta *et al.* (2011) demonstrated significantly higher nitrogen and water absorption in wheat lines with a more vital root system at a depth of up to 0.7 m. Herrera *et al.* (2010) described the importance of the fast growth of the roots in deep soil layers at the beginning of the vegetation period, which may lower nitrogen losses through leaching. The fast growth of the root system of field crops is vital in order to prevent nitrates from leaching to deeper layers of the soil profile, however, the role of the root system in nitrogen uptake efficiency is still a point of controversy (Palta and Watt, 2009). A larger investment by a crop in fine roots that are deeper in the soil and fewer roots in surface layers would improve yields by allowing plants to access additional resources (King *et al.*, 2003). Bertholdsson and Kolodinska Brantestam (2009) showed the importance of early vigour for drought tolerance and the development of finer roots in modern barley cultivars.

It may be concluded that there is a large variation in root system characteristics and the functional strategies of plants within a given species. This is, on the one hand, a positive finding (varietal selection for superior root system traits is possible). On the other hand, it is necessary to factor in varietal differences in the creation and interpretation of experiments. Being critical to the integrity of the plant, the root system parameters affect the efficiency of the whole plant. Roots are very sensitive to soil conditions and are often the first organ of a plant that responds to stress. The adaptability of the root system confirms the excellent ability of roots to change their morphological properties to achieve the optimal growth of the whole plant.

With a degree of generalization, it may be stated that deep-rooted varieties can be recommended in areas with a high water retention capacity in the subsoil. Varieties with a large, shallow root system may be recommended in drier areas with regular, lower amounts of precipitation, during which only the upper layer of the soil profile is moistened (Tron *et al.*, 2015).

### The field phenotyping gap

An ideal method for evaluating root systems should allow the researcher to obtain a detailed characterization of a wide range of root system parameters with a sufficiently large number of measurements. Unfortunately, a universal, inexpensive, reliable and rapid method combining the measurement of the morphological, physiological, quantitative and qualitative properties of root systems in field experiments is not known. A method for the isolation of intact living root systems from soil in fields has not yet been published and would seem to be impossible. For example, biomass estimates from minirhizotrons indicate that the <0.25 mm diameter roots account for nearly 95% of the total root length (Brown *et al.*, 2009).

In general, several basic groups of methods are widely applied for root system evaluation: (i) *in situ* excavation methods (destructive methods – measurements on the same plant cannot be repeated; time-consuming and laborious); evaluation is carried out directly at the site of plant growth, (ii) soil block methods (*ex situ* methods, removal of soil blocks of different sizes from the soil profile; time-consuming and laborious; destructive methods – measurements on the same plant cannot be repeated; allowing the evaluation of the morphological parameters of the root system), the evaluation of the samples takes place in the laboratory, (iii) imaging methods (*in situ* methods such as computed tomography (CT), magnetic resonance imaging (MRI), *etc.*), (iv) electrical methods – methods of measuring electrical capacitance/impedance (*in situ* methods, specified in more detail below); (v) root windows, rhizobox, minirhizotron and rhizotron methods, *i.e.*, *in situ* methods, different-sized glass or plastic containers for plant growth, specifically designed for root system research (Böhm, 1979; Smit *et al.*, 2000).

*In situ* methods are ideal for assessing plant root system properties. *In situ* imaging techniques (CT, MRI) provide a detailed and relatively accurate determination of the size and architecture of the root system. These methods are not affected by error in the form of quantitative losses of root biomass but are limited by the high cost of the measuring devices. These methods also do not allow the evaluation of a large number of plants, and their use under field conditions is unrealistic.

## METHODOLOGY

### Methodological developments, modifications and criticisms of root system electrical capacitance measurement

Another variant of *in situ* measurements, based on measuring the electrical characteristics of the root system, can be used in both laboratory and field conditions when measuring an intact root system. The experience of the authors with this *in situ* method shows that the measurement of root system size by electrical capacitance is ideal for plant species with a root system that is only slightly suberized – for example, the root systems of cereals or some vegetables. Monocots became less suberized than dicots. It should be noted that lignin and suberin deposition is also a natural process in ageing root systems. Ageing roots show a decrease in both electrical capacitance and impedance (Cseresnyés *et al.*, 2013a).

For cereals, a high correlation value is achieved between the root's electrical capacitance and the weight of the root system (Cseresnyés *et al.*, 2018). The probability of the successful selection of a larger root system according to the electrical capacitance is high. In recent years, the size of the root system (measured by electrical capacitance) has been used as a criterion for the selection of genotypes that are tolerant to drought, such as those of spring barley (Chloupek *et al.*, 2010; Svačina *et al.*, 2014) and winter wheat (Heřmanská *et al.*, 2015). It was verified that varieties of wheat and barley with a larger root system size provided higher yields and contained more assimilates (more starch in wheat and barley and more glycid extract in barley) and less nitrogenous substances than those varieties with a smaller root system. This is similar to irrigation in dry conditions (Paynter and Young, 2004). In the experiments of Středa *et al.* (2012), in a dry year, the varieties of wheat that showed the greatest difference in root system size were found to exhibit a yield difference of 860 kg $ha^{-1}$, which translates approximately to the use of an additional 15 mm of subsoil water. However, in some places (in years with above average amounts of precipitation or in wet localities), there was a negative relationship between the size of the root system and the yield. Spring barley requires 293 mm of soil water during its vegetation period (Martyniak, 2008). On the basis of the results of Peltonen-Sainio *et al.* (2011) spring cereal yields decreased by up to 75 kg $ha^{-1}$ due to a decrease in precipitation by 10 mm, and according to the results of Chloupek *et al.* (2010), the 9.5% varietal root system size differences in the case of barley, the increment of the higher root system size to water depletion accounts for 40 out of 293 mm, *i.e.* for about 14% of the total demand.

**Method description**

A prospective *in situ* method with the potential to save money, labour and time is measuring the size of the root system by its electrical capacitance as a part of the electrical impedance. This unique method was originally published by Chloupek (1972) and has been intensively developed at the Mendel University in Brno, Czech Republic (Chloupek *et al.*, 2010; Středa *et al.*, 2012; Středa and Chloupek, 2013; Svačina *et al.*, 2014; Heřmanská *et al.*, 2015) in the last decade. The method is applicable under field conditions and allows the detection of fine structures in the root system. Another field method for the repeated comparative evaluation of the same individual plants at different stages of development with the subsequent possibility of harvesting seeds from the selected plants is not known. The direct link between root system size and yield is an important precondition for successful and practical breeding based on root system properties. However, the influence of soil conditions on the measured results and the inability to directly capture the morphological characteristics of the root system could be disadvantages of this method.

The relationships between the value of the root's electrical capacitance and weight, length, surface or volume of the root system have been demonstrated and published many times (*e.g.*, Rajkai *et al.*, 2005). It has been established that derivation of root system morphology on the basis of electrical capacitance values is not possible (Dietrich *et al.*, 2013). However, the main advantage of this method is the ability to measure hundreds of plants a day and repeat the measurements at different phenological stages. In addition, the measurements are not adversely affected by the roots of neighbouring plants. This is ideal for making a comparison between genotypes and individuals and for selection during breeding under field conditions.

*Theory*

Plant tissue acts as a capacitor when electric current passes through it, this tissue has an electrical capacitance (Cseresnyés *et al.*, 2019; Postic and Doussan, 2016). The magnitude of this electrical capacitance can be measured in physical units – micro- and nanofarads. At the contact surface of two substances that differ in their dielectric constants, a thin double-electric layer develops, and an electric field is formed. The capacitor plates in this case are the root surfaces and the soil environment. The larger the relative area of the capacitor plates, the smaller their mutual distance, the higher the permittivity of the dielectric between the plates, and the greater the electrical capacitance. The permittivity of cellulose increases with water content and this depends on the frequency at which the electrical capacitance is measured. The approximate value of the electrical capacitance for biological membranes is 0.9 $\mu F\ cm^{-2}$ (Montal and Mueller, 1972). This uniform, specific electrical capacitance of biological membranes per unit area inspired Chloupek (1972) to evaluate the relationship between the size of root systems and their electrical capacitance. The closest correlation between electrical capacitance and root system size was experimentally found at a measuring frequency of 1 kHz (Chloupek, 1977). For this reason, the frequency of 1 kHz is most frequently used when measuring the electrical capacitance of root systems. The measured capacitance reflects not only the root system size but also membrane vitality because dying membranes lose their electrical capacitance. The root system shows a high degree of functional activity mainly in the lateral roots. There is an association between the size of the measured electrical capacitance and the developmental stage of plants. Their capacitance increases to its maximum at a certain developmental phase of the plant and then decreases. This is caused by a decrease in the effective area of the roots (suberization of cell walls, necrosis of part of the root biomass), which is able to draw an electric charge. At the same time, there is a relationship between the thickness of cell walls and capacitance. Suberization of cell walls increases their diameter and moves the capacitor plates away from each other; therefore, the measured capacitance becomes smaller. The other reason for the decrease in electrical capacitance is that lignin and suberin have a lower permittivity than the other main component materials of the root. The variability in their quantity causes a considerable variation in the dielectric properties of the root tissue (Cseresnyés *et al.*, 2017). A root system with young active roots therefore has a greater capacitance. An indisputable advantage of the method is that, as a result of biophysical principles, it has the ability to measure even the finest root structures (root hairs).

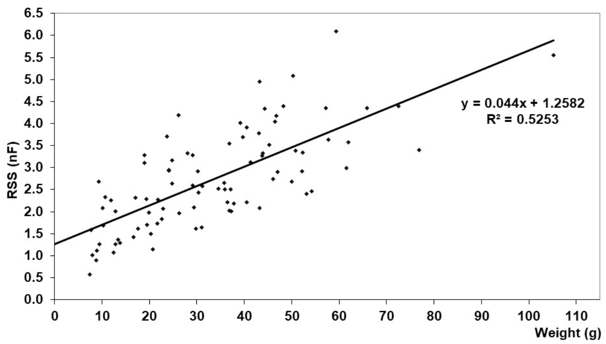


**Fig. 1.** Relationship between electric capacitance and the weight of the main roots of 92 carrot plants (Chloupek *et al.*, 2010).

A simple verification of the relationship between the root system size and the electric capacitance with carrot roots was conducted in the experiment of Chloupek *et al.* (2010). The results showed a significant correlation ($p < 0.001$) between electric capacitance and root weight and root volume, even if the main root was evaluated without lateral rootlets, which contribute substantially to the total surface area of the root. The correlation between electric capacitance and the fresh weight and volume of the roots amounted to $r^2$ value of 0.394-0.525 and 0.388-0.501, respectively, as shown in Fig. 1.

**Root system electrical capacitance – a standardized methodological protocol**

Based on the long-term experience of the authors with the study method, correct results and meaningful interpretation are only possible if standardized measurement principles are followed:

1. A comparison between capacitance values can only be made for measurements on plants of the same species (*e.g.*, *Triticum aestivum*). It is not possible to compare differences between species or within a family (*i.e.*, differences such as *Triticum aestivum* versus *Hordeum vulgare*). Different varieties of the same species may be compared if they are morphologically similar (*e.g.*, number of tillers).

2. When measuring the electrical capacitance of the root system, the plants should be in approximately the same growth phase on the day of measurement, a margin of a few-days difference in the earliness of varieties does not pose a problem. The root system grows more intensively in the vegetative growth phase. Differences in earliness are more critical in the vegetative growth phase.

3. The surface of the measured plant stem must not be wet (drops of water from dew or rain) so that the measuring current does not pass to neighbouring plants in the stand.

4. The soil surface must not be wet (*i.e.*, immediately following rain or with ponding on the soil surface) but it may be moist.

5. It is not possible to compare the differences between plants growing in different substrates. This means that it is only possible to compare plants within one plot thereby keeping soil conditions similar (*e.g.*, the same is true for irrigation). The heterogeneity of the soil conditions between experimental plots must be eliminated by a sufficient number of replicates (plant measurements from more experimental plots or at different sites on the plot). It is not possible to compare the values of root system electrical capacitance from fields far from each other with different soil, agrochemical and soil-climatic conditions. With increasing soil moisture, the electrical capacitance increases. Similarly, soil chemistry (content of ions in the soil) has an effect on the values of electrical capacitance. Nevertheless, some recent studies concerning this topic have proved that soil ion content has a marginal effect on the capacitance-root mass regression.

6. In the case of pot experiment evaluations, it is only possible to compare values from pots with the same substrate (*e.g.*, sand) and the same watering and nutrient addition regimes. Therefore, it is not possible to compare values from variants from, for example, drought stress or fertilizer treatments. Similarly, when assessing the data of the electrical capacitance of roots from hydroponic experiments, a comparison between different concentrations of solutions or solutions of different chemical compositions could produce misleading results.

7. Comparable measurements should be taken on the same day (preferably within a window of several hours) to avoid any dramatic changes in soil conditions, *e.g.*, rainfall, topsoil drying on hot days.

8. An important measurement choice is the relevant growth stage when determining the electrical capacitance of the root system, especially when evaluating yield or production quality. Wang *et al.* (2014) showed that maximum values of root system weight occur in wheat during the flowering stage. With respect to the climatic conditions of central Europe, we propose that the root system should be evaluated during the shooting, heading and grain maturity stages, which are periods when nutrient requirements are at their highest because of the rapid increase in biomass, *i.e.*, for cereals, approximately BBCH 36 (BBCH according to Meier, 1997), BBCH 55 and BBCH 71–73.

9. The distance between electrodes (the electrode in the soil and the electrode located on the plant) has an effect on the measured electrical capacitance. When positioning the soil electrode, it is always important to maintain the same distance from the stem electrode (stem). The ideal distance is 5-10 cm.

10. The position of the stem electrode (distance from the soil surface) must be constant. With increasing distance from the roots, resistance increases and capacitance decreases. When attaching the electrode, it is therefore necessary to keep the distance from the roots as small as possible (Dalton, 1995).

11. It is ideal practice to establish plant stands at regular intervals (*e.g.*, cereals 0.125 × 0.03 m). This arrangement is implemented for convenience and to prevent damage to the adjacent plants. Nevertheless, performing measurements in normal stands (sown at normal stand density) is also possible and the method has been verified. However, in the case of repeated measurements, it is necessary to distinguish (mark) the measured plants from the others.

12. The materials used for measuring the size of a root system via electrical capacitance (Středa and Chloupek, 2013) consist of a digital LCR multimeter, commonly used, *e.g.*, for measuring the capacitance of capacitors. The LCR multimeter is connected to an electrically conductive electrode (soil electrode) and electrically conductive pliers (stem electrode) (Fig. 2). Alternatively, a needle may be used as the stem electrode instead of pliers (*e.g.*, for measuring *Beta vulgaris*, *Brassica napus* var. *napus*, *etc.*). The LCR multimeter parameter settings are as follows: 1 kHz frequency of measurement, parallel capacitance (Cp), measurements in nF (nanofarads). In general, the measured values range from several tenths to nanofarad units. Commercial instruments such as the universal LCR multimeter can be used for these measurements.

13. The construction of the electrodes influences the electrical capacitance values of the roots (Kormanek *et al.*, 2016). In order to evaluate the differences within a single measurement, only the values from one set of electrodes need to be used to perform the root system measurements.

14. One electrode (metal pliers for cereals, alfalfa, *etc.*) or needle (for sunflower, corn, oilseed rape, carrot, sugar beet, *etc.*) must be placed on the plant stem base (1-5 cm above the ground without touching the soil surface). In the case of cereals, it is necessary to grasp (by pliers) the tillers as well because they are not always conductively connected. The other electrode (soil electrode) must be inserted into the soil to a depth of approximately 10 cm, always at the same depth and at the same distance from the measured plant. A deeper placement of the ground electrode increases the measured capacitance of the root system due to the larger contact surface between the electrode and the soil.

15. It is always necessary to measure the electrical capacitance of at least dozens of individual plants (to ensure the sufficiently stable value of the results when comparing varieties). The minimum number of measured individual plants depends on the variability of the soil conditions, the variability of the plot surface and the biological characteristics of the species (uniformity). The degree of variability should be determined by preparatory measurements prior to the start of the main measurements. For cereals from standard small-scale experiments, the minimum number of plants for measurement is 30 per line (at least the number of measuring sites in the canopy multiplied by 10 plants). Repeated evaluations increase the accuracy of the method.

**Fig. 2.** Measuring the electrical capacitance of different crop root system variants with pliers (wheat, mustard, maize, wheat in detail) and with a stem needle (carrot); the schematic of the materials used for measuring root system size via electrical capacitance: a digital LCR multimeter (1), soil electrode (2), connector (3), stem electrode (4).

Obviously, with an increasing number of measured plants (more replications, more measured individuals per replication), the impact of experimental error decreases.

16. Differences between genotypes can be evaluated (i) separately between individual measurement periods (there are differences in the root biomass growth rate between genotypes) or (ii) with the average values for all the measurements (the average value represents the size of the genotype root system over a longer vegetation phase).

## DISCUSSION

### Applications of electrical capacitance in plant breeding

Under dry conditions, the size of the root system was related to grain yield, it showed a response to selection. Spring barley plants with a root system increase of 3.9% exhibited a yield increase of 8.1% in our previous experiment (Svačina *et al.*, 2014) (Fig. 3).

Similarly, in our experiment (Heřmanská *et al.*, 2015), six varieties of winter wheat were mutually crossed, and eighteen populations were sown in the field. For plants of the third and fourth generation ($F_3$ and $F_4$) and their parents, the size of the root system was assessed by measuring its electrical capacitance. The plants with the largest root

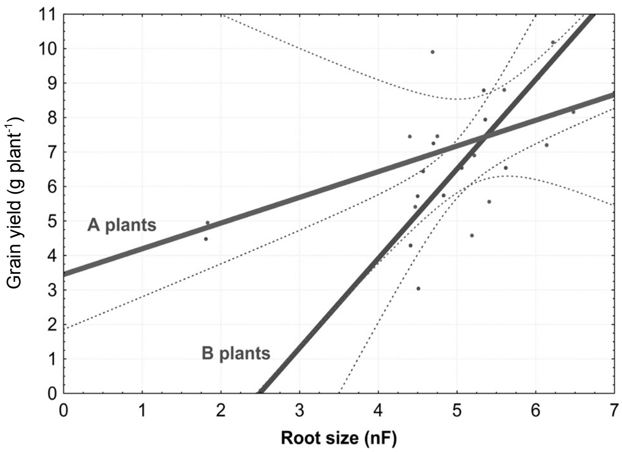


**Fig. 3.** Relationship between root system size and grain yield in selection A (largest roots) and selection B (smallest roots) plants. Scatterplot with regression lines and 95% confidence bands (Svačina *et al.*, 2014).

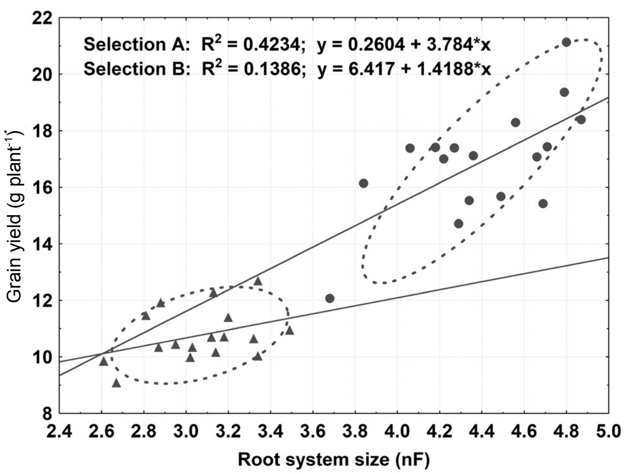


**Fig. 4.** Relationship between the root system size and the yield of winter wheat grains ($F_3$ generation, dry year, average of three locations, the plot is shown with 95% confidence ellipses – the confidence ellipses show where a specified percentage of the data in a scatter plot will lie).

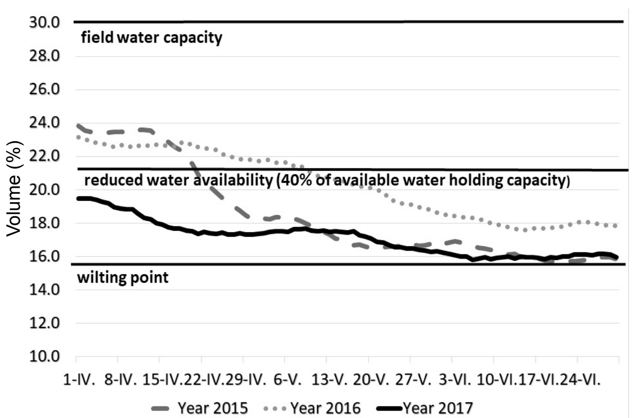


**Fig. 5.** Volume of soil moisture measured by VIRRIB sensors at a depth of 30 cm (Branišovice, 2015-2017).

system (selection A) and with the smallest (selection B) root system were selected. Grains from plants of groups A and B were sown in the next generation. The size of the root system was evaluated in relation to the grain yield in a given generation. The relationship between the size of roots and the grain yield was significant ($p < 0.01$) for selection A ($r^2$ = 0.423, Fig. 4 upper line) but not for selection B ($r^2$ = 0.139, Fig. 4 bottom line). Thus, selection for a larger root system could increase the yield of grain, extract and starch of cereals during dry years and in naturally drier localities.

The aim of our current research (Šmardová *et al.*, 2018) was to evaluate the relationship between the root system size as measured by electrical capacitance in three phenological stages and the wheat grain yield. The root system size and winter wheat grain yield were evaluated in a field experiment at the dry locality of Branišovice (Fig. 5) in the Czech Republic in the years 2015-2017.

The correlation analysis of the relationships between the root system size and grain yield was particularly significant in 2015 (Table 1). Early genotypes created a larger root system at the time of root system size measurement, which was subsequently reflected by an increase in grain yield. Early varieties with rapid initial development, growth, premature flowering, and an overall shorter growing season are able to complete their development and to mature at a time before drought produces a significantly negative impact on grain yields (Blum and Naveh, 1976).

**Table 1.** Relationship between RSS and grain yield of winter wheat expressed by correlation coefficient

| Genotypes | Stage | | | Average |
|---|---|---|---|---|
| | Stem elongation | Heading | Grain filling | |
| | | 2015 | | |
| All (n=39) | 0.414** | 0.161 | 0.159 | 0.394* |
| Late (n=11) | 0.350 | 0.362 | 0.029 | 0.454 |
| Early (n=26) | 0.494* | 0.028 | 0.109 | 0.417* |
| | | 2016 | | |
| All (n=14) | 0.378 | 0.513 | -0.052 | 0.487 |
| Late (n=5) | -0.622 | 0.181 | -0.581 | -0.555 |
| Early (n=9) | 0.452 | 0.579 | 0.066 | 0.661 |
| | | 2015 + 2016 | | |
| All (n=14) | 0.472 | 0.603* | 0.362 | 0.581* |
| Late (n=5) | -0.801 | 0.747 | 0.047 | -0.685 |
| Early (n=9) | 0.663 | 0.439 | 0.413 | 0.784* |
| | | 2017 | | |
| All (n=6) | -0.293 | -0.516 | -0.283 | -0.367 |

All – early and late genotypes, late – late genotypes, early – early genotypes; statistically significant values of correlation coefficient level of: *$p \leq 0.05$, **$p \leq 0.01$.

**Table 2.** Examples of practical use of electrical capacitance for root system parameters by other authors

| Year | Author | Plant species | Experiment type | EC correlated (especially) with |
|---|---|---|---|---|
| 1982 | Kendall | Red clover, Alfalfa | PE, FE | root dry weight; $r^2 = 0.76$ |
| 1995 | Dalton | Tomato | PE | root dry weight; $r^2 = 0.77$ |
| 1998 | van Beem *et al*. | Maize | FE, PE | root fresh mass; $r^2 = 0.56 – 0.73$ |
| 2000 | Psarras and Merwin | Apple | PE | root dry weight; $r^2 = 0.73$ |
| 2004 | Preston *et al*. | Poplar hybrids | PE, FE | root dry mass, root fresh mass; $r^2 = 0.78 – 0.89$ |
| 2005 | Ozier-Lafontaine and Bajazet | Tomato, Amaranthus | PE, H | fresh and dry weight of roots; $r^2 = 0.94 – 0.99$ |
| 2005 | Rajkai *et al*. | Sunflower | PE | root fresh mass, root length; $r^2 = 0.53 – 0.92$ |
| 2005 | Repo *et al*. | Willow | H | root volume |
| 2006 | Čermák *et al*. | 6 woody species | FE | stem basal area, crown projected area; $r^2 = 0.88$ |
| 2006 | Monneveux *et al*. | Maize | FE | |
| 2008 | McBride *et al*. | Maize | H | |
| 2009 | Tsukahara *et al*. | Peach, Japanese pear | FE | root dry mass, fresh mass, root dry mass; $r^2 = 0.81 – 0.89$ |
| 2009 | Vamerali *et al*. | Poplar (several species), Willow | PE | root weight; $r^2 = 0.28$ |
| 2010 | Cao *et al*. | Willow | H | root surface area, number or laterals; r = 0.93 and -0.91 |
| 2010 | Pitre *et al*. | Willow (hybrids) | PE | root dry weight, root biomass; $r^2 = 0.66 – 0.81$ |
| 2011 | Messmer *et al*. | Maize | FE | |
| 2012 | Aulen and Shipley | 10 crop and forage species | PE | root dry mass; $r^2 = 0.30$ |
| 2012 | Dietrich *et al*. | Barley | H | fresh mass, cross-sectional area of nodal and seminal roots; $r^2 = 0.77 – 0.87$ |
| 2012 | Worku *et al*. | Maize | FE | |
| 2013 | Cseresnyés *et al*. | Maize | PE | root dry biomass, root surface area; $r^2 = 0.92 – 0.95$ |
| 2013 | Cseresnyés *et al*. | Maize | PE | root dry mass, root surface area, root length; $r^2 = 0.89 – 0.94$ |
| 2013 | Dietrich *et al*. | Wheat, Barley | PE, FE | root dry mass, stem cross-section; $r^2 = 0.75$ and 0.93 |
| 2013 | Ellis *et al*. | Woody plants (4 species) | FE | root length, root mass, root surface area; $r^2 = 0.71 – 0.99$ |
| 2013 | Ellis *et al*. | Faba bean | PE | root length, root mass, root surface area; $r^2 = 0.21 – 0.31$ |
| 2014 | Cseresnyés *et al*. | Cucumber, Bean | PE | daily transpiration; $r^2 = 0.77$ and 0.89 |
| 2014 | Ebrahimi *et al*. | Wheat (*T. durum* and *T. turanicum*) | FE | |
| 2014 | Nakhforoosh *et al*. | Wheat (several species and varieties) | FE | root length density; r = 0.70 – 0.82 |
| 2014 | Takács *et al*. | Maize, Cucumber, Bean | PE | |
| 2015 | Kormanek *et al*. | European beech | PE | root length, root area, root dry weight; r = 0.50 – 0.82 |
| 2016 | Carlson and Smart | Willow (3 species) and their hybrids | PE | root dry weight, stem dry weight; r = 0.88 and 0.72 |
| 2016 | Cseresnyés *et al*. | Maize, Barnyard grass, Abutilon | PE | root dry mass; $r^2 = 0.90 – 0.96$ |
| 2016 | Cseresnyés *et al*. | Soybean | PE | root dry mass; $r^2 = 0.84 – 0.94$ |
| 2016 | Postic and Doussan | Wheat (*Triticum durum*) | PE | root dry mass; $r^2 = 0.79$ |

**Table 2.** Continuation

| Year | Author | Plant species | Experiment type | EC correlated (especially) with |
|---|---|---|---|---|
| 2016 | Repo *et al*. | Scots pine | PE | |
| 2016 | Sabo *et al*. | Tomato, Bell pepper | PE | |
| 2016 | Sharma and Carena | Maize | FE | plant height, days of silking, number of brace roots; r = 0.3 – 0.46 |
| 2016 | Školníková and Škarpa | Maize | H | root dry matter weight; r = 0.99 |
| 2016 | Wu and Ma | Canola | FE | more parameters of roots; $r^2$ = 0.32 – 0.99 |
| 2017 | Wu *et al*. | Canola | PE | more parameters of roots, r = 0.66 – 0.92 |
| 2018 | Cseresnyés *et al*. | Maize, Soybean | PE, FE | root dry mass; $r^2$ = 0.83 – 0.87 |

PE – pot experiment; FE, field experiment, H – hydroponics; if there is no value in the “EC correlated (especially) with” column, the study was a comparison of species/varieties, r – coefficient of correlation, $r^2$ = coefficient of determination.

From the aforementioned correlation coefficients, it is not always possible to consider a positive relationship between the root system size and the grain yield. In particular, in 2017, the root system did not affect the grain yield; on the contrary, the larger root system had a negative impact on grain yield. In the extraordinarily dry year of 2017, the bigger roots could probably not have given certain plants an advantage, since there was no water available in the soil. In fact, it was quite the opposite, it was a rather useless waste of assimilates. This is a significant contribution to the discussion concerning the impact of root system size on yield in different environments.

Methods for the evaluation of plant root system parameters through the measurement of their electrical capacitance have been successfully used and published by other authors for various plant species. The literature concerning the application of electrical capacitance was reviewed from the first introduction of this method in 1972. Some examples of the practical use of the method for evaluating monocotyledonous species, including cereals, dicotyledonous plants and woody plants, are shown below (Table 2).

## SUMMARY

Agricultural research and plant breeding are particularly concerned with the results of research carried out under field conditions, which often differ significantly from laboratory experiments or pot trials. The unique method of root system electrical capacitance measurement allows for both the accurate and repeated evaluation as well as the harvesting of selected plants under field conditions. A comprehensive review of root system electrical capacitance in plant breeding research and applications in a diverse range of crops will highlight the important role of this simple field method in the current plant phenotyping landscape.

The method of plant root system evaluation under field conditions described in this study, which is particularly useful for root phenotyping, has been applied both in research and practice many times. Based on the long-term experience of the authors with the method, correct results and meaningful interpretation are only possible if the standardized measurement principles described are followed in full. From the experiences described here, the standardization of the method, including certain mandatory procedures, is proposed. The optimization of the methods, the identification of weak points and the elimination of their negative impacts on the results of the evaluation is thus guaranteed.

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