Plant and Soil **48**, 525–532 (1977) Ms. 3152

EVALUATION OF THE SIZE OF A PLANT'S ROOT SYSTEM USING ITS ELECTRICAL CAPACITANCE

by OLDŘICH CHLOUPEK

Plant Breeding Station, 664 43 Želešice near Brno, Czechoslovakia

SUMMARY

This paper extends an earlier one[5]. The relationship between electrical capacitance of a plant root system (C) and size (weight, volume, surface) of the root system (x) can be expressed by equation of the line

$$C = a + bx,$$

if *a* equals size of parasitic capacitance of measurement, i.e. capacitance of soil, wires, *etc.* and *b* equals regression coefficient influenced by type of soil plant species, measuring frequency and voltage, *etc.*

For practical purposes of size evaluation of root systems, *e.g.* in plant breeding, direct measured values of electrical capacitance (C) can be used when relative comparison is sufficient. For more precise experiments the values of *a* and regression coefficients *b* can be calculated.

INTRODUCTION

This paper extends the results published earlier[5] and gives reason for the method.

Campbell, Phillips and O'Reilly[4] constructed an instrument for electronical measurement of pasture yield *in situ*. In principle the instrument is a electrical capacitance meter and plants introduced into the system induce a change of electrical capacitance which is measured. The size of the change is related to the quantity of herbage. The instrument reflected about 90% of variation in herbage yield of both dry and organic matter.

The method of these authors was extended by other workers often using modified instruments[1 2 3 11 12 13 14 16 17 21].

RESULTS AND DISCUSSION

For measurement of capacitance an impedance bridge (Tesla BM 394 E) was used which enables higher values of loss factor tan δ to be balanced. The bridge is fed by batteries and therefore suitable for use in field conditions. This instrument is set on 1 kHz frequency, measures until 12 V, by maximal consumption of 15 mA. It employs a standard mica capacitor which was thermally compensated.

The first investigation was into the relationship between the size of living tissue and its electrical capacitance in constant conditions. Potato tubers were dipped into pure spring water in glass in such a way that on the upper part of tuber formed a small island. Into this island one electrode was pricked to a depth of 1 cm. The second electrode was placed in the water not to touching the tuber. In this way electrical capacitance was measured in parallel. Linear correlation coefficient (r) of fresh weight of tubers on their electrical capacitance by 0.1 kHz was 0.775, by 1 kHz 0.710 and by 10 kHz 0.560 ($n = 17$). The size of living plant tissue was therefore coherent with its electrical capacitance.

The relationship between the size of root systems and their electrical capacitance was studied with a number of plant species under various conditions and evaluated by means of regression analysis[5]. The method may be verified using an easily conducted experiment with carrots (*Daucus carota* L.). Details are given when the experiment was conducted in a loam field. The capacitance of the root system was measured with one terminal of the impedance bridge connected to the basal part of petiols and the second one earthed by an underground electrode about 20 cm from the plant at a depth of 10 cm. The measurement was carried out at two stages of growth and at two percentages of moisture of soil (some of the plants were measured and weighed; then the soil was watered and the capacitance of more roots measured and weighed). Only the spherical root (enlarged hypocotyl) without small lateral roots was weighed.

The overall correlation coefficient in experiments I–IV (Table 1) between the root electrical capacitance and weight was 0.717 accounting for about 50% of the variation. The regression coefficients in the separate experiments did not differ significantly from each other. The relationship between electrical capacitance and fresh

TABLE 1

The estimation of the relationship between the fresh weight of spherical root of carrot and its electrical capacitance in relation to the soil

	Experiment No				Overall
	I	II	III	IV	
Days from sowing	89	89	140	140	
Soil moisture (weight %)	11	25	19	27	
Correlation coefficient r	0.630	0.469	0.637	0.621	0.717
Significance of r. Value of P	0.001	0.001	0.001	0.001	0.001
Regression coefficient (b_{yx})	1.164	1.748	1.615	1.555	2.040
Standard deviation of regression (Sb_y)	0.174	0.405	0.287	0.292	0.187
Value a (pF)	99	117	95	253	

In the column overall are values of all plants like it would be only one experiment. Y = electrical capacitance.

TABLE 2

The group means of weights of spherical carrot roots and adequate electrical capacitance

Interval of weight (g)	Mean weight (g)	Mean electr. capacitance (pF)	Interval of weight (g)	Mean weight (g)	Mean electr. capacitance (pF)
2–7	4.45	89.60	37–45	40.60	199.30
8–16	11.70	126.20	45–59	52.00	184.05
17–22	19.00	144.15	59–71	64.50	277.60
22–26	23.80	154.25	72–97	83.80	293.80
26–33	29.65	165.95	100–136	113.45	353.00
33–37	34.75	181.35	138–340	202.85	512.15

In each group an average of 20 plants is given, in the last group of 13 plants.

weight of roots was evidently principally linear (Table 2) and did not intersect the origin of co-ordinate axes as was the case in an experiment of Lovett and Burch[17].

It was probably caused by parasitic capacitance, *i.e.* by capacitance of wires and soil. In the Experiments I–II, or III–IV (Table 1), the increase of parasitic capacitance, *i.e.* value, in which the regression line crosses the coordinate y (value *a*) in dependence to the increased soil moisture caused by higher soil capacitance can be seen.

This phenomenon was tested by a simple experiment. The electrical capacitance of quartz sand and loam soil was measured between two iron plates in plastic cylinder using variable moisture of the substrate (Table 3).

It is clear that electrical capacitance of loam soil was higher than that of quartz sand and it increased in both cases in dependence to moisture increased. These results conform different size of value a in experiment No. 2 and 3 in the paper published earlier[5], due to its higher value in loam soil than in sand.

TABLE 3

Electrical capacitance and loss factor of loam soil and quartz sand of different moisture measured between two iron plates at a distance of 50 mm*

Loam soil			Quartz sand		
Moisture (weight %)	El. capacit. (pF)	Loss fact. (relat.)	Moisture (weight %)	El. capacit. (pF)	Loss fact. (relat.)
5.71	22.5	100	2.78	9.15	100
10.11	104.7	92	5.56	31.60	59
14.52	236.0	82	8.57	43.10	56
18.92	552.0	118	11.43	52.00	67
23.32	805.0	170	14.40	76.30	71

* To compare: Electrical capacitance of potato tuber mass at a distance of 10.8 mm between the same plates was 5,420 pF.

In the following section the action of some factors of measurement is evaluated. In these results the relationship between root system size and its electrical capacitance can be seen.

An earthing system of several electrodes placed around plant was compared with a single electrode in experiment with sun-flowers. The average relationship between fresh and dry weight of roots and electrical capacitance did not change ($r = 0.741$ for multiple electrodes and 0.744 for a single electrode). The influence of distance of the earth electrode from a measured plant was also small over a distances of 5–15 cm (at a distance of 5 cm the correlation coefficient between fresh weight of roots and electrical capacitance was 0.723, at a distance of 10 cm 0.737 and at a distance of 15 cm 0.752; also the regression coefficients did not differ significantly: 1166, 1192 and 1193 pF/g; $n = 15$).

To avoid the possibility of influencing the results by direct current of plant (by biopotential) an air plate capacitor was connected between the plant and the bridge. In the experiment with 15 sunflowers in sand the relationship between capacitance and root weight did not change ($r = 0.948$ and 0.951 respectively).

Larger correlation coefficients between electrical capacitance and weight were obtained when measurements were made in parallel than in series combination of the instrument. In an experiment with 15 sun-flower plants the influence of current frequency was tested on relationship between weight of root systems and their electrical capacitance. The correlation coefficient was with 0,8 kHz 0.803 and by 5 kHz 0.948.

The influence of herbage on capacitance measurements was estimated in an experiment with two varieties of red clover growing in a field. The electrical capacitance was measured with the herbage intact; the herbage was then removed and the capacitance immediately remeasured using the same electrical connections. In cv. Kvarta the electrical capacitance before defoliation was 281 pF (a mean of 50 plants) and after decapitation 290 pF. In cv. Perenta was 256 and 265 pF respectively. These differences were not statistically significant. However, the electrical capacitance of the root system changed over a longer period of time after defoliation. The following data were obtained with cv. Hungaropoly (mean of 50 plants): two hours prior to defoliation 167 pF, two hours after defoliation 278 pF, after 21 hours 291 pF, after 44 hours 245 pF and 93 hours after decapitation 242 pF. These changes can be explained as resulting from the continued absorption of water by roots while the rate of transpiration was decreased. In this way a greater quantity of water occurred in the roots perhaps, also resulted in larger volume of roots. Only after some time did absorption and hydratation of roots decrease.

In experiments with plants of red clover, potato and mustard leaves of neighbouring plants touched each other. Electrical capacitance of roots of individual plants evidently was not affected because in these experiments significant relationship between the electrical capacitance and the quantity of herbage, tubers or seeds of individual plants was also found[6 7 8 9]. The contact resistance between dry leaves was probably so high that the relatively small current used in measuring capacitance did not cross to the adjoining plant or did not induce any polarization.

From the experiment reported on page 2 and 3 and in Tables 1 and 2 and from the preceding paragraphs it can be concluded that a significant relationship between size of root system and its electrical capacitance in relation to the soil exists. But a problem arises to the nature of this dielectric. To answer this question we estimated the linearity of the dependence of the dielectric on the voltage used in its measurement. Electrical capacitance as function of voltage and frequency is given in Table 4.

From Table 4 it is evident that the capacitance (C) did not increase linearly with the voltage for all investigated frequencies. The course of all curves has the characteristic shape of saturation. Such a type of polarization occurs in materials consisting of iont moleculs if they are able to turn in direction of external electrical field.

TABLE 4

The electrical capacitance (C) at measuring voltage (U) and frequency (f) in plants growing in soil

Plant	Number of plants	f (Hz)	C (pF) at voltage 0.1 V	1 V	10 V
Onion	15	100	188.0	206.6	207.4
		500	61.3	67.0	68.0
Oat (at shoot formation)	10	100	236.1	263.4	263.9
		1000	87.8	87.2	90.9
		10000	20.4	22.8	22.8
Mustard (plants with 2–3 pairs of leaves)	10	100	56.85	59.16	62.65
		1000	20.31	21.95	22.24
		10000	11.58	12.96	13.03
Mustard (at flowering)	10	100	171.4	174.9	180.1
		1000	41.55	43.82	46.68
		10000	23.13	24.76	25.87

The soil cannot contribute to the capacitance of the system (roots–soil) because of its great electrical conductance. It is clear from the measured values of tan δ of the soil. Boundary layer between root and soil and of membranes in roots made up the imaginary component *i.e.* electrical capacitance. If only the electrical capacitance of boundary layer between root and soil (membranes) was measured, the values would be much higher because the electrical capacitance of membrane amounts to 0,9 $\mu F\ cm^{-2} \pm 20\%$ (*e.g.* Pliquett[19]) as surface of root systems approaches an area of several

m^2 (*e.g.* Kolosov[15]). It is therefore also necessary to consider the capacitance of cell membranes inside of roots which connected in series puts up a considerable resistance to the current going through it. Plant roots are namely organs in which are cell dipols connected in series[18]. The measured electrical capacitance depended therefore not only surface of roots but also their contents.

The suggested method of root system evaluation also enabled the dielectric dispersion of mustard roots to be related to their yield of seeds[8]. Plants that gave the highest yield showed, from the beginning of growth until the end of flowering time, the lowest dispersion (ratio of electrical capacitance at 1 kHz and at 10 kHz) and after flowering time the highest dispersion. This dispersion was greater towards the end of vegetation.

If the method of electronical evaluation of herbage yield published by Campbell *et al.*[4] is compared with the suggested method of measuring root systems it can be seen that the principle is the same. The results that measure the relationship between electrical capacitance and root size or yield are similar. But there is a difference in manner of the measurement. In the method of measuring root systems electrical capacitance is measured by means of an electronic bridge, a most accurate method. In Campbell *et al.*[4] it is measured by means of resonance frequency. Because of this certain differences occur. In the present results the frequency in range from 0,8 to 5 kHz was used, in the Campbells method a considerable higher frequency, mostly about 3 MHz was used.

In the method described in this paper the measurement in the range of α dispersion may have induced polarization of cells[20], membranes and large cell particles[19]. Jones and Haydock[14] consider in the Campbell's method the space under electrodes as large number of capacitors connected in series with the plant matter situated between them. According to this explanation the dielectric is the air and 'plates' of individual capacitor are plant matter. The herbage part is therefore measured indirect, while in our method root system is measured direct, the dielectric consisting of all plant roots.

ACKNOWLEDGEMENTS

The author is grateful to Prof. Dr. M. Bauer for advices from electronics and Dr. A. Troughton for reviewing the manuscript.

Received 6 April 1976

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