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A measurement system for determining temperature, water potential and aeration of growth medium

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TIIVISTELMÄ: KASVUALUSTAN LÄMPÖTILAN, VESIPOTENTIAALIN JA ILMANVAIHDON MITTAUSJÄRJESTELMÄ

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A measurement system developed for the parallel and real-time measurement of temperature, matric potential and oxygen diffusion rate (ODR) of a growth medium was assessed. The system consisted of a portable computer, a datalogger, temperature sensors, tensiometers and an ODR-meter with Pt-sensors.

For the measurements, proper sensor contact with the growth medium was needed. For matric potential measurement, appropriate shape and material of the tensiometer tips should be selected for different measurement purposes. The determination of oxygen diffusion rate is based on single, non-continuous measurements. The ODR-measurement required special care with the insertion and handling of the electrodes and selection of the applied voltage. The ODR-measurement of a coarse peat medium was applicable only at matric potentials > –5 kPa. This measurement system was shown to be useful and suitable for accurate determination of thermal-, water- and aeration conditions of a growth medium under greenhouse conditions.

Kasvualustan lämpötilan, matriisipotentiaalin ja hapen diffuusiovirran yhtäaikaista ja viiveetöntä mittaamista tutkittiin tarkoitusta varten rakennetulla sähköisellä mittausjärjestelmällä. Mittausjärjestelmä koostui kannettavasta mikrotietokoneesta, dataloggerista, lämpötila-antureista, tensiometreistä sekä hapendiffuusiomittarista platina-elektrodeineen.

Mittaukset edellyttivät huolellista anturien käsittelyä ja hyvää kontaktia mitattavan kasvualustan kanssa. Tensiometrikärkien materiaalin ja muotoilun tulee olla tarkoituksenmukaiset matriisipotentiaalin mittaamiseen eri sovellutustilanteissa. Hapen diffuusiovirran mittaus perustuu kertamittauksiin ja se vaati erityistä huomiota platinaelektrodien käytössä ja mittausjännitteen valinnassa. Hapen diffuusiovirran mittaus soveltui kasvuturpeelle, kun matriisipotentiaali oli > –5 kPa. Mittaussysteemi todettiin suhteellisen helppokäyttöiseksi, nopeaksi ja tarkaksi kasvihuoneoloissa ja siten soveltuvaksi kasvualustan lämpö-, vesi- ja ilmanvaihto-olojen määrittämiseen.

Keywords: matric potential, oxygen, diffusion, peat, sensors, growing media.
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1 Introduction

In a growth medium, the most important physical factors affecting plant growth are the thermal-, water- and aeration conditions. These conditions, and the need for their manipulation, can be evaluated by measuring the values of the variables that affect them. For studying the physical growth conditions in different growth media and managements, such as nursery practices and site preparations, it is crucial to have an easy, fast and accurate system for measuring the values of the physical variables in-situ.

Temperature near the ground surface and in the growth medium can be easily measured by electrical sensors (Taylor and Jackson 1986). The matric potential (in kPa), which is measured by tensiometers, has usually been used as a variable describing the water status in soil (Cassel and Klute 1986). Often tensiometers are still read by vacuum gauges or Hg-manometers, but they more commonly have been integrated into electrical pressure sensors and automatized data-acquisition systems (Long 1984, Cassel and Klute 1986, Lowery et al. 1986, Phene et al. 1989, Saarinen 1989, Nyhan and Drennon 1990). In the case of aeration, the indices and measurements vary more and are also more complex (Mcintyre 1970, Stolzy 1974, Glinski and Stepniewski 1985). However, the best index for soil aeration has been regarded to be the oxygen diffusion rate (ODR, $\mu g/m^2s$), which can be measured electrically with Pt-electrodes (Mcintyre 1970, Glinski and Stepniewski 1985, Mannerkoski 1985).

This paper describes a portable system for parallel and real-time determination of temperature, matric potential and oxygen diffusion rate of a growth medium. The measurement system, which is based on measurement sensors, a personal computer and a datalogger, was tested under greenhouse conditions.

2 Material and methods

2.1 Measurement system

Datalogger

The portable measurement system was integrated on a datalogger Datataker 100F (DT100F) (Fig. 1). The DT100F is a field model that includes 23 differential or 46 single analog and 8 digital input channels. There are 1 analog and 8 digital output channels. The analog input channels can be used for measuring voltage, current, resistance, temperature and frequency. In this study, the sockets of the input channels were connected to the internal amplifiers with wrapping wires so that the input was of the differential voltage type for the sensors used. The analog input channels are autoranging (within ± 25, 250, 2500 mV). The accuracy of the input channels for the voltage is 0.15 % with a resolution of 1 µV. The accuracy and resolution were found to be clearly greater than those of the responses (in mV) of the measurement sensors. The electrical terminals of the sensors were connected with shielded cables to the input channels of the datalogger. The power (12VDC) to the DT100F (operable also on the internal battery) was supplied from a common electrical net via a 220VAC/12VDC adapter. The power (12VDC) to the pressure and temperature sensors was supplied from a common electrical net via a discrete constant voltage source (Mascot, 220VAC/± 12VDC). The supply current was 60 µA for a temperature sensor, 1 mA for a Motorola pressure sensor and 2 mA for the Micro Switch pressure sensors used. The DT100F includes a multiplexer and an A/D-converter.

The datalogger was operated on the software (DECIPHER) delivered with the datalogger. The software was run and the datalogger was programmed from a portable personal computer (Toshiba T3100SX) by entering commands of ASCII-characters via a RS232C-interface. The sensor responses (mV) scanned from the datalogger output were retrieved and stored in files on the hard disk of the computer.

Temperature sensors

Temperature was measured using semiconductor sensors (National LM35DZ). The measurement scale of the sensors is 0 to 100 °C. The sensors were calibrated against a Hg-thermometer (Fuess) at room and electric oven temperatures. In the calibration was included also the fundamental fixed reference points of the melting point of ice (0 °C) and the boiling point of water (100 °C) (Taylor and Jackson 1986).

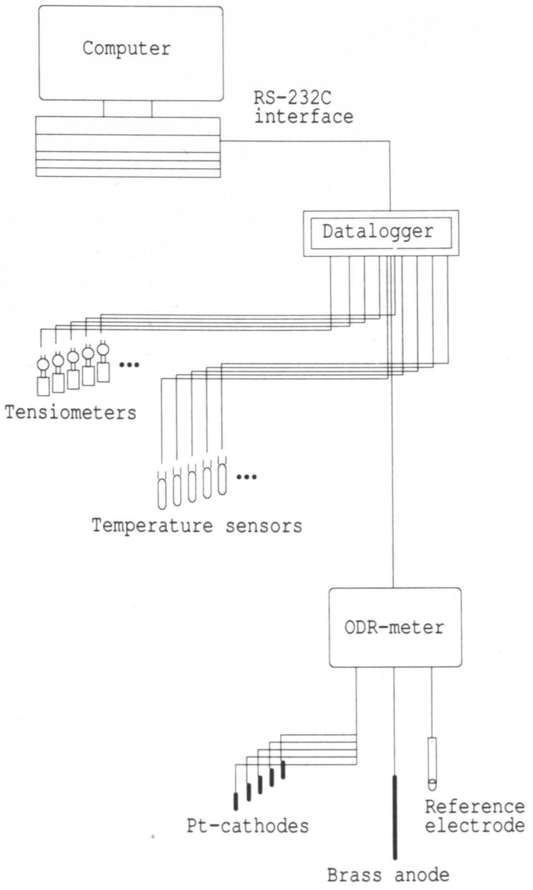

Fig. 1. Schematic diagram of the measurement system.

Matric potential sensors

The matric potential of the growth medium was measured by tensiometers. To test the effect of different tensiometers on the measurement of the growth medium, three different pressure sensors and three differently shaped porous tips were used (Fig. 2). The tip materials in the thin and thick types were ceramics (bubbling pressure 100 kPa, SoilMoisture Equipment Corp.); in the wide type a sintered glass was used (11–16 µm in pore size, corresponding to a bubbling pressure of about 15 kPa, SCHOTT and Gen Mainz.). When a tensiometer is inserted into a growth medium and equilibrium is achieved between the growth medium water and the tensiometer water through the porous tip, the water pressure (in kPa) inside the tensiometer sensed by a pressure sensor (in mV) describes directly the matric potential in the growth medium. To avoid the effects of fluctuations in temperature and atmospheric pressure on the responses of the sensors, differential (temperature- and barometric pressure-compensated) pressure sensors (Micro Switch 16PC15DF and 136PC15G1, Motorola MPX2050GVP) were used. The measurement scale of the Micro Switch sensors is ± 103 kPa and that of the Motorola sensor ± 50 kPa against the ambient pressure. According to the manufacturers, the accuracy of the sensor outputs is within ± 1.5 (Motorola and Micro Switch 136PC) and ± 3.0 mV (Micro Switch 16PC) of the full scale output.

At the high potential range of 5 to –15 kPa, in which the relative reading error is great, each pressure sensor was calibrated. The calibration was done by making direct comparisons (with 10 replicate) between the pressures sensed with a sensor and the hydraulic heads (Cassel and Klute 1986), which were adjusted with the hanging water column in plastic tubing connected to a sensor. The response times of the tensiometers were determined as the time required for the response of a pressure sensor to become constant (± 0.01 mV) when the hydraulic head was rapidly adjusted from 0 to –9.8 kPa.

Oxygen diffusion rate-meter

The oxygen diffusion rate (ODR) was measured using Pt-electrodes (E7.0, Jensen Instruments). The electrodes cannot be connected directly to the datalogger; they need a reference electrode (Ag/AgCl) and a brass anode connected to an appropriate electrical circuit, for which an ODR-meter (Model D, Jensen Instruments) was used. When the electrical voltage is applied to the ODR-meter, the oxygen starts to reduce at the Pt-cathode, which in turn causes a corresponding current. The observed cathode current is proportional to the ODR (Mcintyre 1970, Glinski and Stepniewski 1985). In order to ensure

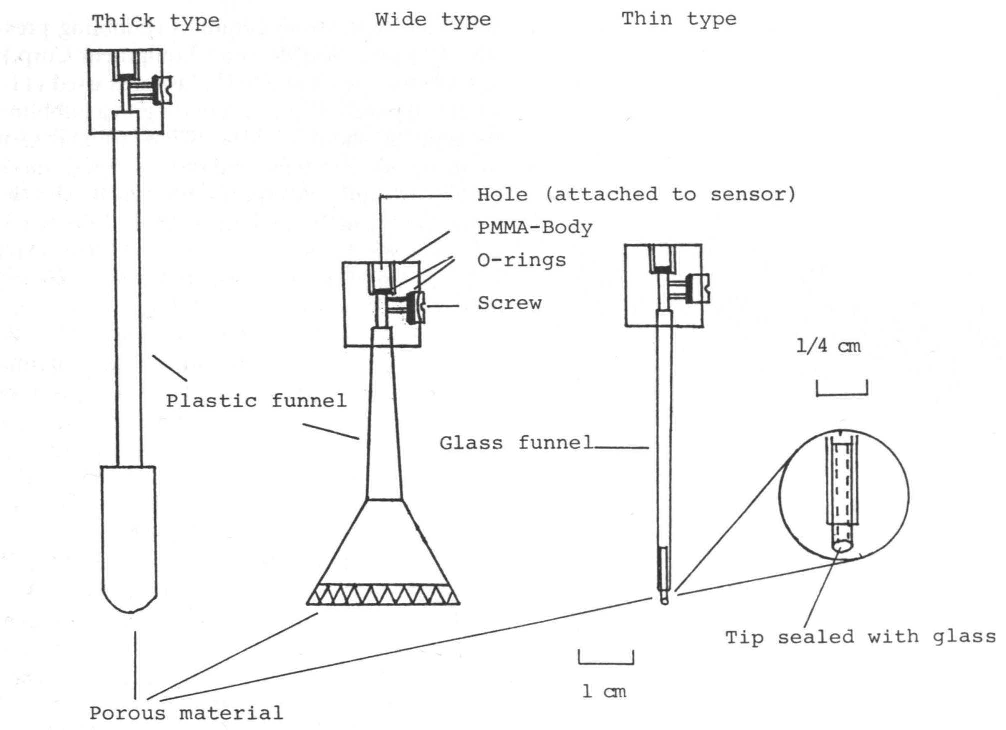

Fig. 2. Schematic diagram showing the construction of the tensiometer tips tested.

oxygen reduction at the electrodes, the electrodes must be covered with a water film while measurements are being taken. The electrode current obtained is affected, in addition to O_2 concentration, by soil structure, pH, salt concentration, moisture and applied voltage (e.g. Mcintyre 1970, Mannerkoski 1985).

When the growth medium was being measured, the distance between each Pt-electrode was at least 1.5 cm. The electrode current was observed each time after 4 minutes stabilizing time from insertion and application of the voltage of –800 mV (Mannerkoski 1985). The current (µA) (surface area of an electrode ~ 0.085 cm^2) was converted to the corresponding ODR-value (µg/m^2s) by multiplying it by the constant 9.83, which was calculated from Formula 1 (Mcintyre 1970, Glinski and Stepniewski 1985). Between measurements, the electrodes were stored in dry air at room temperature. No appropriate reference methods were available for testing the accuracy of the ODR-meter.

$$ODR = (M\,i)\,(n\,F\,A)^{-1}, \text{ where} \qquad (1)$$

M = molecular mass of O_2 (32 g mol^{-1}),
i = current intensity (µA),
n = number of electrons consumed per mole of O_2 (= 4),
F = the Faraday constant (96500 C mol^{-1}),
A = electrode area (m^2).

The ODR-meter system was not yet available with a computer interface; therefore it was not possible to connect the system directly to the datalogger input channels and to have completely automatic data retrieval from all the Pt-electrodes. In addition, ODR could not be recorded continuously, because, due to their 'poisoning' by precipitation of certain compounds, the Pt-electrodes cannot be left in the growth medium for long periods (Mcintyre 1970, Glinski and Stepniewski 1985, cf. Campbell 1980). So far, only one reading at a time can be retrieved from the ODR-meter into the datalogger by connecting the plotter output of the ODR-meter to one datalogger input. This connection was used, when the Pt-electrodes were connected in parallel. The resulting single response (regarded as a value describing the mean response from the bulk growth medium) could be monitored from the datalogger.

2.2 Test measurements

To assess the applicability of the system, a coarse-graded (Puustjärvi 1982) and premix-fertilized Finnish (VAPO D) *Sphagnum* peat growth medium (see Heiskanen 1990) filled into a PVC-plastic sample core (d = 15 cm, h = 12 cm) was used for test measurements. The pH of the growth medium, which was measured from the extracted water, was 4.7–5.0. The measurement sensors were inserted horizontally into the growth medium through small drill holes in the core wall. The tips of the sensors were about 3 cm from the core wall and 6 cm from the surface of the peat. Before the measurements, the desired levels of matric potential were achieved by allowing the growth medium to equilibrate with the respective water (distilled) table levels for two or three days. The measurements were made indoors at temperatures between 20 and 25 °C.

Regression analysis was used to test the responses of the sensors. Statistical and graphical data were analyzed using SYSTAT (v. 5.0) software (SYSTAT... 1990).

3 Results and discussion

3.1 Temperature measurement

The response of the sensor used in relation to a Hg-thermometer was linear (y = 10.5 x, R^2 = 0.999) with deviation from the line being < 0.45 °C at temperatures lower than 80 °C (Fig. 3). For more precise measurements, even greater accuracy can be achieved by calibration with a calorimeter. The temperature sensors are calibrated by the manufacturer directly to the linear relation of 10.0 mV/°C, in which the error of the response is typically within ± 0.9 °C over the whole measurement scale. The sensors are small and easy to handle and no difficulties were encountered in measuring the temperature of the growth medium.

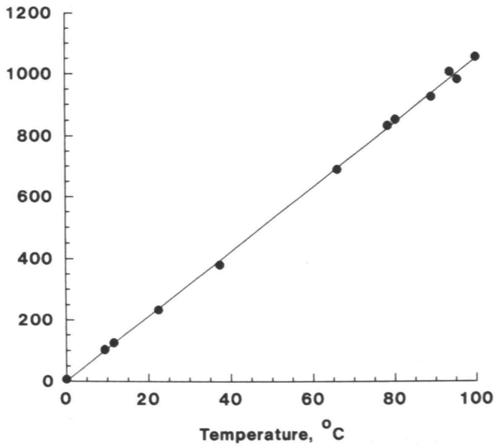

Fig. 3. Calibration line of a National LM35DZ temperature sensor. On the y-axis is the sensor response (mV) and on the x-axis is the temperature read from a Hg-thermometer (°C).

3.2 Matric potential measurement

The responses (mV) of the pressure sensors were linear (Long 1984, Phene et al. 1989) at the matric potential range of 5 to –15 kPa used (Fig. 4, Table 1). The calibration lines passed near the origin, because the responses were achieved from the zero-offset situation (at 0 kPa). The slope of the Motorola sensor line was clearly gentler and the standard deviations somewhat higher than those of the Micro Switch sensors. The standard deviations of the sensor responses (each determined from 10 measurements) were small, less than 0.07 mV. The responses in the vertical and horizontal sensor positions did not differ markedly (Table 1), which indicated that within the potential range used, the differences between the two positions in the hydraulic heads in the adjusting water tubing were small.

When the different types of porous tips were used, the tensiometers responded to a matric potential change (from 0 to –9.8 kPa) in different ways (Fig. 5, Table 2). In particular, the physical dimensions of the porous tips affected the response time. With a large surface area, the contact area between the surrounding water and the tensiometer water was large and equilibrium

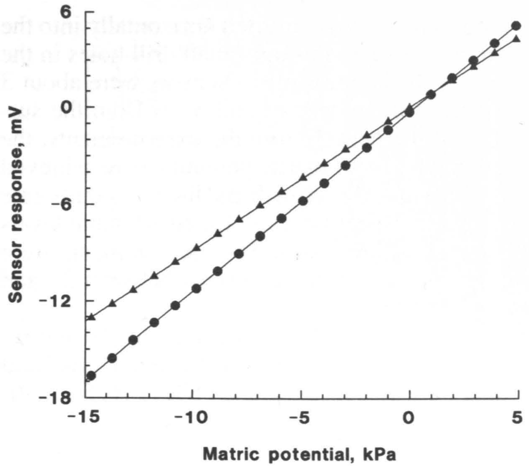

Fig. 4. Calibration line of a Micro Switch 16PC15DF (circles) and a Motorola MPX2050GVP (triangles) pressure sensor placed vertically to the water tubing used for adjustment of hydraulic head. On the y-axis is the sensor response (mV) and on the x-axis is the matric potential (kPa) in the tubing. Standard deviations (from 10 measurements) at different potentials are less than 0.044. (Micro Switch 136PC15G1 response almost the same as 16PC15DF, see Table 1).

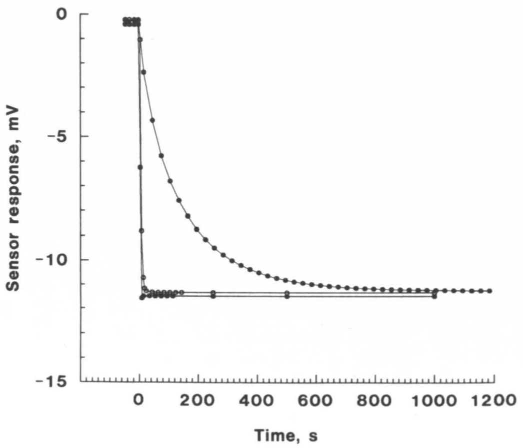

Fig. 5. Sensor response (mV) in time (s) to the matric potential altered from 0 to –9.8 kPa and from a time of 0 s from three tensiometer tips measured with a Micro Switch 16PC15DF sensor. (Curves: upper = thin tip, middle = thick tip and lower = wide tip. See Fig. 2).

Table 1. Parameters of linear regression equations (y = ax) showing the relationship between the matric potential x (kPa) and the electrical output response y (mV) for the three single pressure sensors placed vertically and horizontally to the water tubing in which the hydraulic head was regulated. The response at each matric potential level (between 4.9 and –14.7 kPa) is the mean of ten repeated measurements at desorption. Sensors: A = Micro Switch 16PC15DF, B = Micro Switch 136PC15G1, C = Motorola MPX2050GVP.

Sensor	a	R^2	p	SD*
Vertically				
A	1.1351	0.9994	< 0.00005	0.004–0.020
B	1.1331	0.9998	< 0.00005	0.005–0.044
C	0.8855	0.9999	< 0.00005	0.015–0.036
Horizontally				
A	1.1363	0.9997	< 0.00005	0.005–0.028
B	1.1270	0.9999	< 0.00005	0.007–0.036
C	0.8812	0.9999	< 0.00005	0.032–0.074

* Standard deviations at different matric potentials.

Table 2. Characteristics of the three tensiometer tips tested.

Tip type	Wall thickness	Surface area (Inner wall)	Response time*
	mm	mm^2	s
Wide	3.7	530	13
Thick	3.5	340	53
Thin	0.3	3	1280 (21.3 min)

* Total time required for sensor output to stabilize (± 0.01 mV) when the matric potential was rapidly altered from 0 to –9.8 kPa.

was achieved rapidly, within tens of seconds (c.f. Nyhan and Drennon 1990). With the thin-type tensiometer the contact area was very small and the response was therefore slow (> 20 minutes). The responses of the tensiometers also differed in the peat growth medium at desorption (Fig. 6). The thick-type tensiometer responded almost linearly ($y = 1.146\ x$, $R^2 = 0.996$), which is close to the calibration line for a single sensor (see Table 1). The slight deviations of the response lines (Fig. 6) from linearity were due to the heterogeneity of the growth medium and, possibly, to incomplete equilibrium of the matric potential. The response of the wide-type tensiometer became almost constant when the matric potential was below –10 kPa, which is close to the bubbling pressure limit of the sintered glass tip. The response of the thin-type tensiometer increased at matric potentials below –9 kPa, which shows that the contact between the ceramic tip and the growth medium has broken. Thus, very small tensiometer tips could be most useful in conditions where the water content fluctuates slowly and when the growth medium samples are small and fine-textured. The porous material used in the tensiometer tips should also be selected so that the bubbling pressure is high enough.

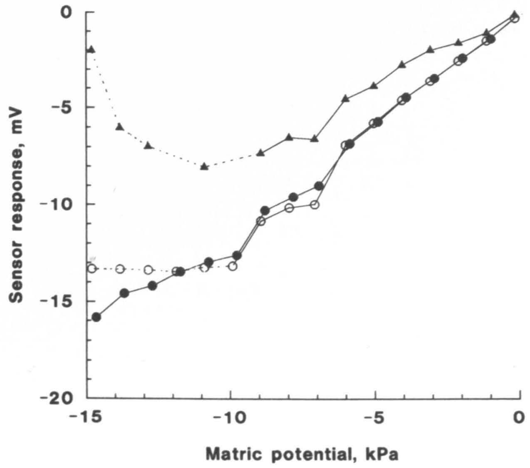

Fig. 6. Sensor responses (mV) of three tensiometers placed horizontally in the peat medium to the decreasing matric potential (kPa) adjusted with a hydraulic head. (Tensiometers are: thick type with a Micro Switch 16PC15DF sensor (solid circles), wide type with a Micro Switch 136PC15G1 sensor (open circles) and thin type with a Motorola MPX2050GVP sensor (solid triangles)). The dotted lines deviate markedly from the response with a single sensor (see Table 1).

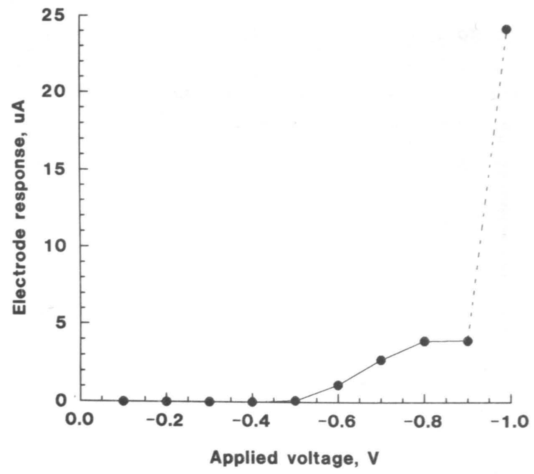

Fig. 7. Response (mA) of five Pt-electrodes to the different applied voltages (V) measured from the peat medium using the D-model ODR-meter (Jensen Instruments). Before each measurement at decreasing applied voltage, the Pt-electrodes were removed from the medium and washed with water. The standard deviations at the different voltages (from 0 to –0.8) are less than 0.2. The matric potential in the peat was 0 kPa. The dotted line shows a drastic, unstable rise in the electrode response.

3.3 Oxygen diffusion rate-measurement

Oxygen diffusion rate was measured with one electrode or with several electrodes at a time connected in parallel. The current observed from parallel electrodes can be regarded as a mean response from the growth medium (the current must be divided by the number of parallel electrodes). The ODR-meter, however, was found to be capable of measuring the electrode current only as high as about 85 µA (with the nominal maximum being 50 µA) per electrode or per set of parallel electrodes. Therefore, the parallel connection of electrodes can be used in such measurements where the sum of the electrode currents is less than 85 µA. The current of 85 µA with one electrode suffices for measuring an ODR-value of about 830 $\mu g/m^2s$ or with five parallel electrodes of about 165 $\mu g/m^2s$.

The ODR of the growth medium was measured using an applied voltage of –0.8 V, which was found to be within the plateau range (–0.75...–0.90 V) of the relationship between the electrode current and the applied voltage (Fig. 7). With voltages higher than –0.5 V, the current was very low (± 0). The applied voltage of –0.99 V gave strong current (with a SD being as high as 17.8), which may indicate that the

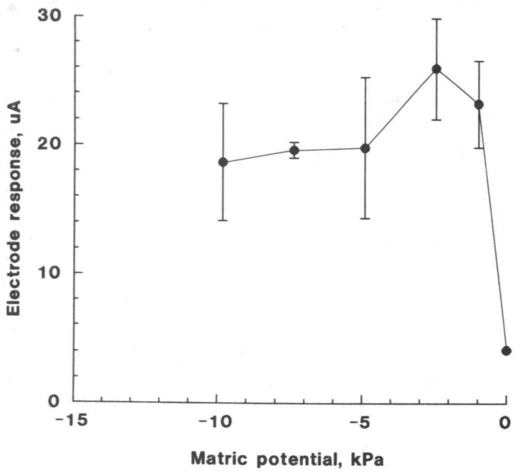

Fig. 8. Mean response of five Pt-electrodes to the decreasing matric potential using the D-model ODR-meter and an applied voltage of –0.8 V. The vertical bars indicate standard deviation (at 0 kPa, the SD is 0.07).

systems does not work stably with such a low voltage. Mannerkoski (1985) also used –0.8 V as the applied voltage for *Sphagnum* peat. However, lower applied voltages have been used both for mineral soils (e.g. Mcintyre 1970, Glinski and Stepniewski 1985) and for organic soils (Campbell 1980). The plateau range measured is also shorter than that usually reported for mineral soils (Mcintyre 1970, Glinski and Stepniewski 1985, Mannerkoski 1985), which may be affected by the acidity (pH < 5.0) of the peat (see Mannerkoski 1985).

When the matric potential of the growth medium was below –2.5 to –5 kPa, the observed electrode current tended to decrease (Fig. 8), despite the fact that the aeration improves during desorption. This was due to drying of the electrode surfaces. Mannerkoski (1985) reported that in peat the observed current decreased when the water table reached 50 cm (~ –5 kPa), which is similar to the result achieved in this study. The variation in ODR was great, however, which is typical of ODR-measurements in general (e.g. Mannerkoski 1985). In mineral soils, ODR can usually be measured at matric potentials from saturation to –50 to –100 kPa (Glinski and Stepniewski 1985). Due to the coarse structure and large pores of the peat, the measured ODR decreased, beginning from higher matric potentials than in fine-textured soils. This is because the air-filled porosity increases more in peat during drying and therefore the water film covering the electrodes also dries earlier in peat than in fine-textured mineral soils. Hence, with peat growth medium the ODR-measurement is applicable when the matric potential is higher than about –5 kPa.

Favourable ODR-values for plant growth are usually above 70 $\mu g/m^2s$. For most plants the critical ODR-value is about 30 $\mu g/m^2s$ (Glinski and Stepniewski 1985). This critical value corresponds to an electrode current of about 3 μA, which in this study was found to occur in peat growth medium at matric potentials of 0 to –0.5 kPa.

4 Conclusions

The measurement system described was shown to be useful and applicable for determination of thermal-, water- and aeration conditions in growth medium under greenhouse conditions. The measurements can be made rapidly, relatively easily in real-time and in parallel. During the measurements, there must be proper sensor contact with the growth medium. For matric potential measurement, the shape and material of tensiometer tips must be selected to ensure that they are appropriate for different measurement situations. The determination of oxygen diffusion rate is based on single, non-continuous measurements. The ODR-measurement requires special care with the insertion and handling of the electrodes, selection of the applied voltage and interpretation of the results. The ODR-measurement of coarse peat growth media can be applied to matric potentials of > –5 kPa.

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