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The Wageningen Rhizolab – a facility to study soil-root-shoot-atmosphere interactions in crops

I. Description of main functions

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Abstract

A research facility is described for the integrated study of soil-root-shoot-atmosphere relationships in crops. The Wageningen Rhizolab has been in use since 1990, and consists of two rows, each with eight below-ground compartments aligned along a corridor. A rain shelter automatically covers the experimental area at the start of rainfall. Compartments are 125 cm × 125 cm and 200 cm deep. Each compartment has a separate drip irrigation system. Crop canopy photosynthesis, respiration, and transpiration can be measured simultaneously and continuously on four out of eight compartments at a time. Each compartment can be filled with a selected soil material (repacked soil) and is accessible from the corridor over its full depth. Multiple sensors for measuring soil moisture status, electrical conductivity, temperature, soil respiration, trace gases and oxygen are installed in spatial patterns in accordance with the requirements of the experiments. Sensors are connected to control and data-acquisition devices. Likewise, provisions have been made to sample manually the soil solution and soil atmosphere. Root observation tubes (minirhizotrons) are installed horizontally at depth intervals ranging from 5 cm (upper soil layers) to 25 cm (below 1 m). The facility is at present in use to study growth and development of vegetation (crops) in relation to drought, nutrient status, soil-borne diseases, and underground root competition. One important application is the study of elevated CO_2 concentration and climate change and the way they affect crops and their carbon economy. Growth and development of field grown vegetables and winter cover crops are also evaluated. The common aspect of those studies is to gain a better understanding of crop growth under varying environmental conditions, and to collect datasets that may help to improve mechanistic crop growth simulation models that can address suboptimal growth conditions.

Introduction

Over the past decades plant growth and crop productivity have been studied extensively to assess their potential production. Investigations often concentrated upon non-limiting growth conditions and primary processes such as photosynthesis and respiration of single leaves, plants or crops, or else they studied aspects such as canopy structure, light interception and dry matter partitioning in above ground plant organs. Less attention was given to the interaction between shoots and roots. In this respect methodological problems encountered in the study of underground plant parts (Böhm, 1979) have restricted progress.

Growing concern about environmental effects of agricultural production practices requires that the primary objective of agricultural research be shifted from maximizing yield as such to realizing an optimum uti-

lization of resources, with emphasis on sustainability and reduced use of chemicals and nutrients and their emission to the environment. This requires more information on plant and crop performance under suboptimal growth conditions such as those imposed by biotic factors (diseases, pests and weeds) and abiotic factors (nutrients, water, temperature, aeration, soil structure). Consequences of intercropping and competition between plants in a stand or vegetation or between weeds and crop plants are also attracting new research efforts.

These developments have led the DLO- Institute for Agrobiology and Soil Fertility, and Departments of the Wageningen Agricultural University (Theoretical Production Ecology and Agronomy) to develop a joint research facility which enables a simultaneous quantification of both over- and underground plant processes and their interaction. The Wageningen Rhizolab was developed from the concept of a rhizotron (Hilton et al., 1969; Rogers, 1969; Taylor, 1969; Taylor et al., 1972). It includes a range of standardized and novel equipment to monitor soil processes and crop performance with a high temporal and spatial resolution. It has some parallels with the SPAR units like those in use in the USA (Acock et al., 1985; Jones et al., 1984) but differs in essential points with respect to air conditioning and control of atmospheric composition, accessibility of the soil compartments and emphasis on monitoring of root/soil processes. Its design and technical features are described in this paper, and some results illustrate its applications. Detailed results of the experiments will be published separately.

General design and principle functions

Experimental units and ground plan

The Wageningen Rhizolab consists of two rows of eight experimental units each, sunk into the soil, spaced along a central underground corridor (Fig. 1). The corridor is aligned along an east- west axis to limit possible effects of position-dependent differences in shading due to the presence of posts of the framework supporting the moveable shelter (Fig. 2).

The soil compartments are 125 cm × 125 cm and 200 cm deep, with a concrete bottom and walls, except the one facing the corridor. The latter consists of removable wooden panels. Access ports can be made at various positions to accommodate instruments that can be serviced from the corridor. The compartments are spaced along the corridor leaving in between a net distance of 95 cm for a guard crop. The guard crop can be grown all around the compartment, also in containers on top of the ceiling of the corridor as this is 30 cm below the soil level. The situation thus closely simulates field conditions (Fig. 3). The ceiling, including the container-grown guard plants, can be lifted during measurements to give access to the root observation tubes in shallow soil layers.

Soil compartment

Each compartment can be filled with repacked soil of a selected soil type. Alternatively, cylindrical columns (80 to 110 cm diameter) containing an undisturbed soil could also be placed in the compartments (Belford, 1979). The compartments are filled layer by layer with moist soil, each layer (5 cm) being compacted to the required density. Samples are taken to verify the result. Relevant soil characteristics such as water potential curves are determined separately. Sensors are installed during filling (Fig. 4). Wiring and tubing are placed horizontally, to minimize the creation of preferential channels for water flow and root penetration. The cables come together to a sealed feed-through in the wooden panel. The part of the compartments (about 50 cm) remote from the corridor is kept free of sensors to allow the soil volume to be sampled by augers. An overview of the standardized numbers and positions of sensors and other equipment introduced into the soil is given in Table 1. Sensors may be added according to the requirement of the specific experiments.

Rain shelter

A rain shelter unfolds as soon as rain is detected. The rain shelter has been designed to close sufficiently fast such that not more than a maximum of 1.5 mm precipitation will reach the crop in the experimental units, even from sudden and exceptionally heavy showers which normally occur less than once a year. Additionally vertical screens unfold at the sides towards the prevailing wind direction, to prevent rain from being blown in. The total area protected against rain measures about 9.5 × 25 m. This is wider than the net area occupied by the central corridor and the compartments at both sides.

The stack of translucent roof panels is stored at the North side to prevent shading of the experimental area. In dry conditions only the supporting frame remains over the compartments (Fig. 2). With this design only

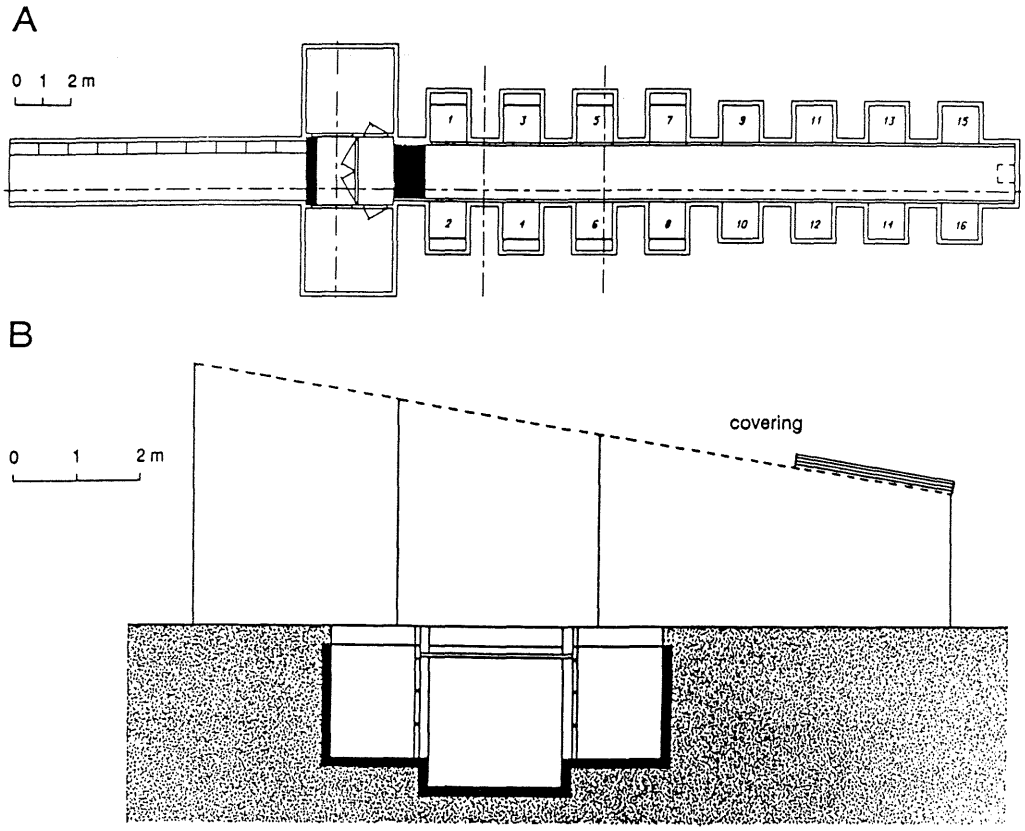

Fig. 1. Floor plan (**A**) and transverse section (**B**) of the underground construction of the Wageningen Rhizolab. In the transverse section (B) the central corridor is shown, with a soil compartment at both sides, separated from the corridor by wooden panels. A 30-cm deep soil container over the corridor allows the growth of a guard crop all around the compartments.

a minimal deviation from the climate conditions prevailing in the open field is expected.

Water balance

The inside of the soil compartments are lined with a thick polythene film, to prevent water loss and minimize air leakage. Each compartment is provided with a drain at the bottom and an individual drip irrigation system, which can be operated automatically (Fig. 5, #21, 14). The set of 15 liter reservoirs for irrigation, placed in the corridor (Fig. 6), can be filled to the required level and nutrients added as required. The water is delivered, at once or in split doses, to the drip irrigation system by applying pressure to the reservoir under command of the control system. Electrodes, sensing the water level in the reservoir, protect the irrigation lines from being blocked by air entry. The irrigation tubes are installed at the soil surface at mutual distances of 20 cm and their water outlets are spaced at 10 cm, thus giving a distribution pattern of 20 × 10 cm.

The Wageningen Rhizolab is equipped with 160 sensors (distributed over the compartments) that simultaneously measure soil moisture content, soil temperature, and electrical conductivity in different soil layers (Fig. 5, #15). Per ten sensors a multiplexer is scanning the positions, and eight multiplexers are coupled to one computer controlled unit. In recent years developments have concentrated on automated measurements using TDR (Dalton and Van Genugten, 1986), but at the time the Rhizolab was built the reliability and possibility for automated measurements at many points simultaneously was still under development, and an operational alternative was chosen. In this system the measurement of soil moisture is based on the measurement of the same physical parameter, the dielectric constant, as with TDR. Changes in the volumetric water content are dominated by the dielectric constant of water (about 80, whereas that for dry soil is less than 5). The dielectric constant of the soil is measured using the capacitance between electrodes with the soil as dielectric. In contrast with TDR this is done at a fixed frequency (20 MHz) (Hilhorst et al., 1992).

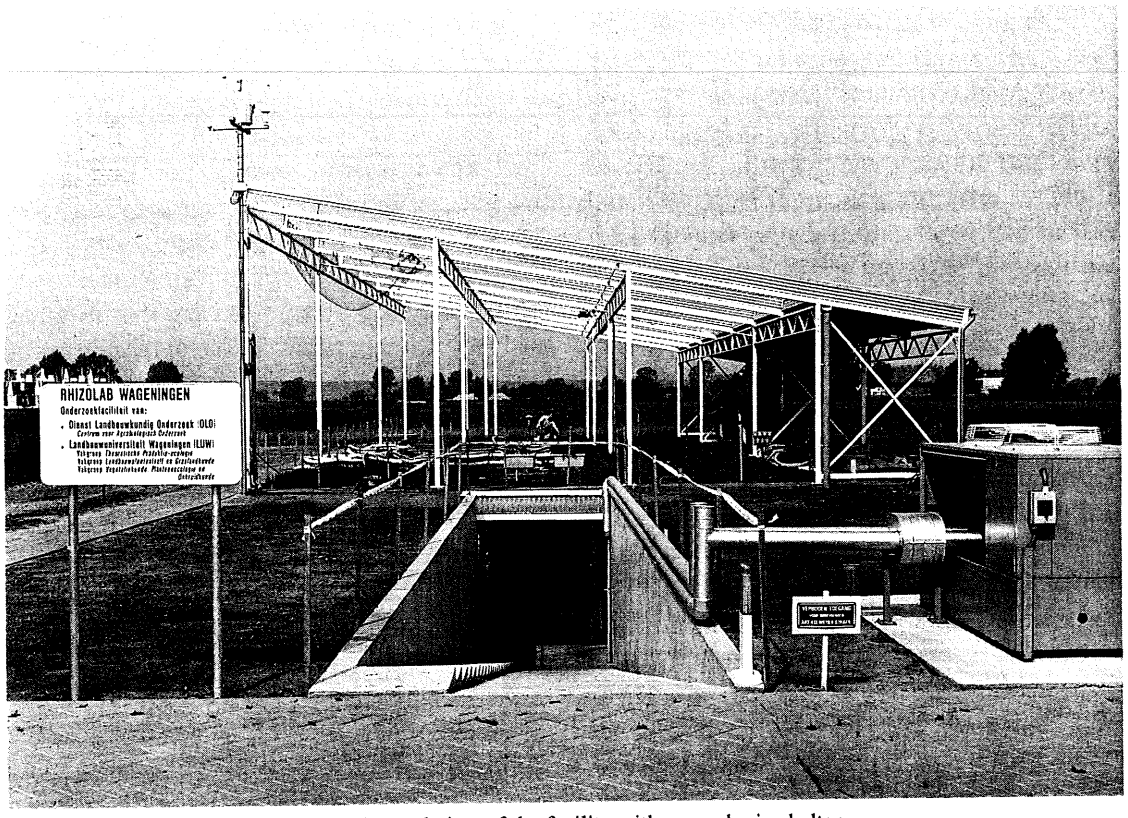

Fig. 2. General view of the facility with opened rain shelter.

Fig. 3. Details of the experimental units, showing the canopy enclosures with a wheat crop (front) and open plots with a potato crop (back). The stack of roof panels can be seen in the back.

Fig. 4. Placement of sensors and sampling points in the soil compartment during filling. 1: suction cup, 2: gas exchange cell, 3: microporous tubing, 4: tensiometer, 5: capacitance moisture sensor.

The dielectric constant can be converted to volumetric water content for the given soil. A typical calibration curve obtained from a soil using different moisture content is shown in Figure 7. Electric conductance (up to 2 mS/cm) is measured with the same sensor as part of its conductivity compensation technique (Hilhorst, 1984).

In parallel, the soil water potential is determined using 48 tensiometers (ceramic elements 6 cm long, 1.8 cm diameter), distributed over the 16 compartments (Fig. 5, #20). Two tubes (pvc pressure tubing for medical applications) run from the tensiometer across the corridor wall, where one is connected to an electronic flow-through pressure transducer (Micro Switch, 156PC; 0–15 psi, Honeywell) and the other is sealed and used to purge the tensiometer.

A fixed water table can also be maintained by using a Mariotte system (Tomar and O'Toole, 1980) connected to the drain (Fig. 5, #21).

Soil solution, temperature and soil atmosphere

Soil solution is extracted with a vacuum line and ceramic suction cups (Fig. 5, #18) (5.5 cm long, 2.2 cm diameter) or hydrophylic microporous tubing (length 50 cm, diameter (outer) 0.25 cm, (inner) 0.14 cm) (Meijboom and Van Noordwijk, 1992). A ceramic cup yields data on concentrations of nutrients (NO_3^-, K^+)

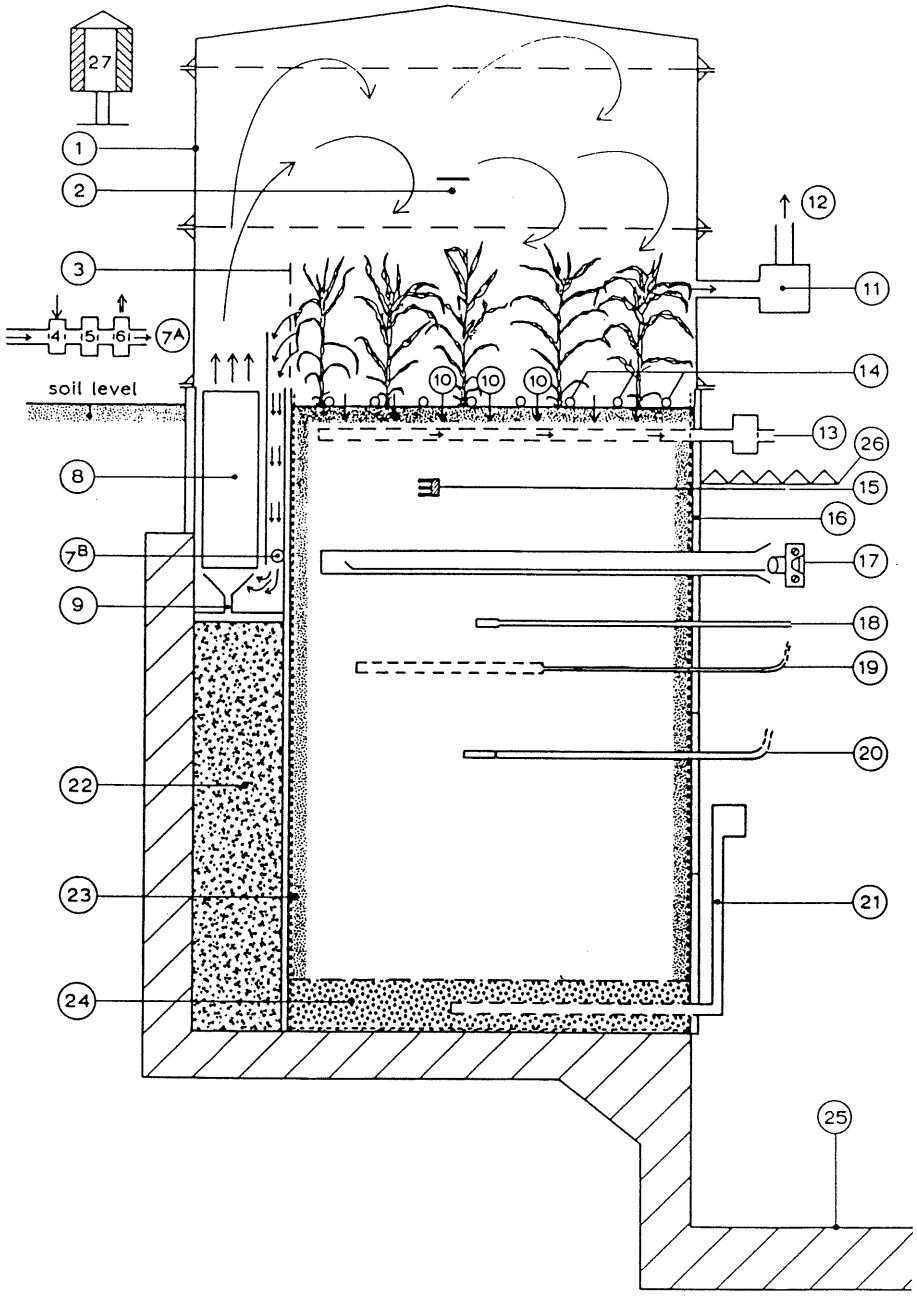

Fig. 5. General scheme of a compartment with installed canopy enclosure, sensors and minirhizotrons: 1. Crop enclosure (two segments of each 50 cm stacked). 2. Shielded temperature sensor. 3. Shading screen to simulate canopy effects at convector side. 4. Blower for refreshment air/CO_2 injection point. 5. Air flow meter/mixing with added CO_2. 6. Sampling point of refreshment air for water vapor and CO_2. 7a/7b. Air inlet for refreshment air (connecting tube not shown). 8. Convector unit for air conditioning. 9. Collection point for condensation water. 10. Air flow into the soil. 11. Sampling point for CO_2 and water vapor. 12. Adjustable air vent. 13. Air drain, flow meter and CO_2 sampling. 14. Drip irrigation system. 15. Sensors for moisture (capacitance), temperature and electric conductivity (5–20; typically 10 per compartment). 16. Wooden panels, allowing acces from corridor. 17. Root observation tube with video-camera (5–20; typically 11 tubes per compartment). 18. Suction cups and microporous tubing (5–20; typically each 16 per compartment). 19. Gas exchange chamber (O_2, CO_2 in soil atmosphere). 20. Tensiometers (2–5 per compartment). 21. Mariotte-system for water table adjustment. 22. Inert material (sand) below convector. 23. Water tight plastic bag, for water table experiments. 24. Filter bed and drainage. The floor is sloped, and the drain placed at the lowest point. 25. Corridor: floor. 26. Corridor: ceiling. 27. Meteo station (global radiation, temperature, rain-event detector, rainfall, relative humidity, wind direction and speed).

Table 1. Standard numbers and depths of various sensors, samplers and minirhizotron tubes in the compartments

Depth (cm)	Mini-rhizotron	Capac. sensor	Tensio-meter	Ceram. cup	Microp. tubing	Gas exch. Cell	Thermo-Couple	Air drain[a]
5	1	2	–	2	2	2	1	–
10	1	–	–	–	–	–	–	–
15	1	2	1	2	2	2	1	1
20	1	–	–	–	–	–	–	–
25	–	1	1	2	2	2	5	–
30	1	–	–	–	–	–	–	–
40	–	1	1	2	2	2	1	–
45	1	–	–	–	–	–	–	–
60	1	1	1	2	2	2	5	–
80	1	–	–	–	–	–	–	–
85	–	1	1	2	2	2	3	–
100	1	–	–	–	–	–	–	–
110	–	–	–	–	–	–	–	1
115	–	1	1	2	2	2	–	–
120	–	–	–	–	–	–	3	–
125	1	–	–	–	–	–	–	–
150	1	1	–	2	2	2	–	–
180	–	–	–	–	–	–	–	1[b]
Total	11	10	6	16	16	16	19	3

[a]In normal conditions only the drain at 15 cm is used. If this is stoppered, the soil profile down to 110 cm or 180 cm can be flushed with air from the canopy enclosure.
[b]The drain at 180 cm is normally used to drain excess water from the profile, or install a water table (see section Water balance and Fig. 5, #21).

in soil solution surrounding a particular point in the profile (Grossman and Udluft 1991), whereas microporous tubing will collect solution from a long cylindrical volume of soil. At least 16 sampling points (Table 1) are distributed over the soil volume in each compartment.

To manually sample the composition of the soil atmosphere (CO_2, O_2 and trace gases), 16 gas exchange cells are placed in the soil (Fig. 5, #19). The cells (2.5 cm diameter, 2.5 cm long) are made of cut disposable syringes. The opening of the cell is covered with screen gauze; the intact end of the syringe is connected (luer lock) to 1-mm inner diameter air tight microtubing (viton) that runs across the wall into the corridor.

Readings of soil temperature are obtained from a sensor built into the capacitive soil moisture sensors described above (providing 160 points) and from thermocouples (simultaneously max. 60). Temperature deviations in the corridor caused a horizontal temperature gradient in the compartments, which, at a depth of −60 cm, appeared to be maximally 1°K from a point close to the wooden panels to the middle of the compartment. At smaller depths differences diminished. If required, the soil in individual compartments can be cooled or heated by passing coolant through tubing buried in the compartments (Groenwold and Van de Geijn, 1990).

Rooting pattern dynamics

Root growth and distribution is studied using a mini color videocamera (Bartz Technology Company, Santa Barbara, CA, USA) sliding into the horizontally installed root observation tubes (Fig. 5, #17; glass minirhizotrons, outer diameter 6 cm). The minirhizotrons are 130 cm long, protruding from the wooden panels through a sealed feed-through into the corridor (Fig. 6), and penetrating the soil volume almost to the far end. They are closed (test-tube shaped) at one end, to prevent disturbance of the soil atmosphere (aeration, water loss). Between measurements 40 cm

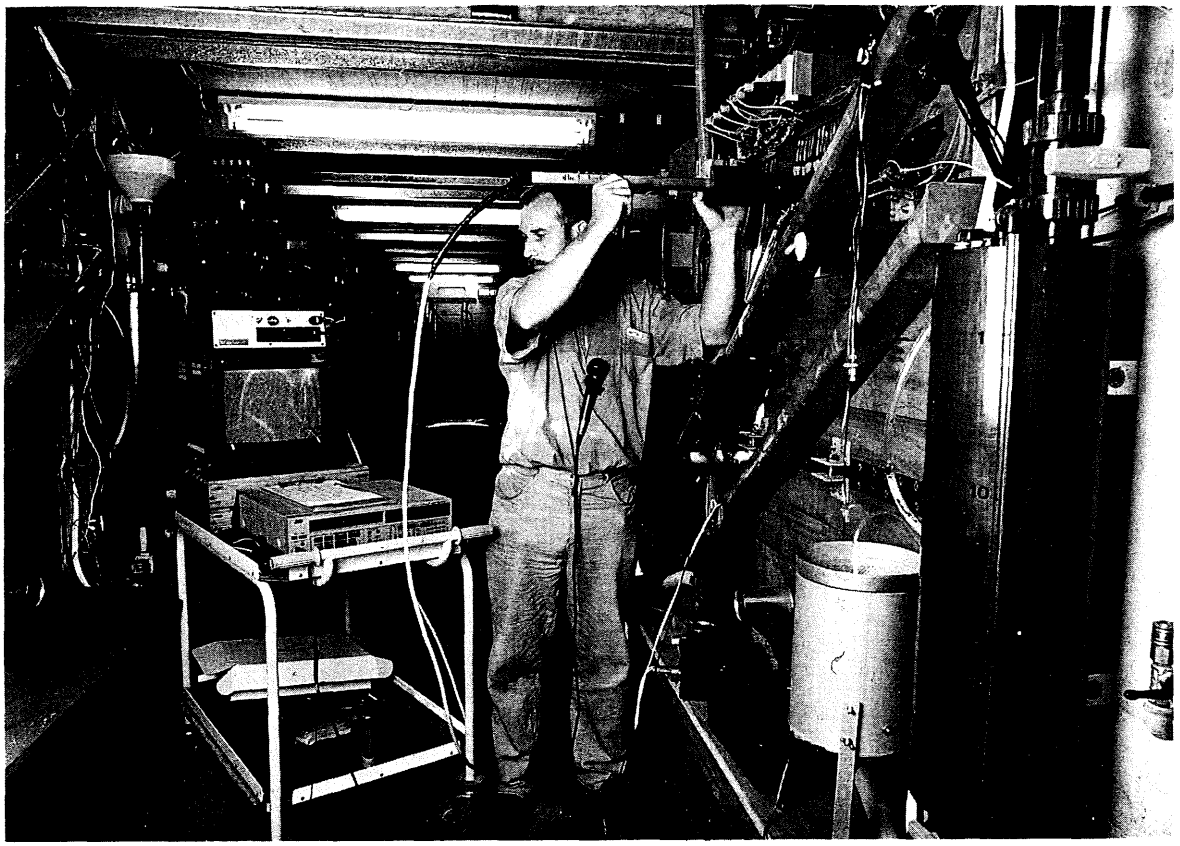

Fig. 6. Underground corridor with instrumentation, irrigation tanks and access ports of minirhizotrons during recording of rooting patterns using the videocamera.

of cylindrical foam rubber is inserted into the opening to limit temperature differences relative to the bulk soil and prevent condensation in the minirhizotron due to temperature differences (Smit et al., 1994a). The horizontal position has been chosen to minimize the risk of roots preferentially following the tubes after hitting the glass surface due to gravitropism, as is often observed in classical rhizotrons provided with glass walls. In the configuration used the roots hitting the glass surface will follow the periphery only for a short distance, and move away acording to their normal directionality. Moreover, the positions of the minirhizotrons has been chosen such as to minimize mutual shading (Smit et al., 1994). Minimum distance between minirhizotrons in the vertical direction is 40 cm.

Video-images (13 mm × 18 mm) can be recorded, using either visible light or UV-fluorescence. In the latter mode optical contrast between soil and roots may be improved. To analyse the dynamics of the root system, the appearance and decay of individual roots can be followed from stored video images. This gives access to a quantification of root turnover during the season (Box et al., 1992; Chen et al., 1991; Van Noordwijk et al., 1993).

The standard methodology to study root systems in the Rhizolab is by analysing video recordings in minirhizotrons, supplemented and calibrated with some analyses on soil samples and roots recovered from the soil via sampling and washing (Smit et al., 1994a; Vos and Groenwold, 1987). Destructive soil samples are taken from a strip of 50 cm width parallel to, but most remote from the corridor (the 'rear end' of the containers). Sampling holes are immediately refilled with similar soil. Normally samples are taken no more than three times per growing season with four replications per compartment using an auger of 5 cm diameter (root length determination) or 2 cm diameter (nutrients).

Weather data

As part of the facility (Fig. 5, #27), a weather station records radiation, windspeed, rainfall, relative humidity and soil and air temperature. Additional measuring channels are available, for instance to monitor leaf tem-

perature in the crop. The rain-event detector providing the signal to close the translucent rain shelter is also part of the weather station.

Canopy enclosures and air conditioning

Gas exchange measurements of the crop canopy can be made by fitting a transparent enclosure (polycarbonate, 5 mm) with minimum leakage on the top of the walls of the compartments (Fig. 5, #1). Temperature and CO_2 concentration in the enclosure can be controlled. Four independent enclosures can be operated simultaneously, and fitted on eight of the 16 experimental units. The height of the enclosures can be adapted to plant height by stacking segments of 50 cm each (up to 250 cm).

The canopy enclosures are essentially operated as a sunlit "open system". A small air conditioner cools or heats the air (Fig. 5, #8) and circulates it constantly, enabling each enclosure to be operated at a selected temperature regime. Capacity of the air conditioner allows patterns between plus and minus 10°K different from ambient. Air circulates in the enclosure at about 800 $m^3.hr^{-1}$. Fresh air is brought in at a measured rate of about 50 m^3 per hour (Fig. 5, #7a connected to #7b), and a small pressure head (200–400 pascal) is maintained by minimizing leaks and adjusting the vent (Fig. 5, #12). This pressure head eliminates back-diffusion of CO_2 from the soil. Some 20 m^3 air per hour is flowing into the soil, which escapes through an "air-drain" consisting of three parallel lines (distance 50 cm) buried at about 15 cm depth (Table 1, Fig. 5, #13).

The Wageningen Rhizolab allows short-term or prolonged (season long) exposure of the canopy to a CO_2 enriched atmosphere (Van de Geijn et al., 1993). Temperatures can follow a preset day/night pattern, or track ambient temperatures, if required, with a constant or variable offset.

Evapotranspiration, photosynthesis and soil gas-exchange

While using the crop enclosures for days or months, photosynthesis, respiration and evapotranspiration of the crop are determined at 10-minute intervals for each enclosure. To this end, the flow of refreshment air (see above) is measured at the inlet (Fig. 5, #5). Differences in CO_2 concentration and water vapour between the air inlet point and the bulk air in the enclosure allow the canopy gas exchange rate to be determined. To complete the crop water balance, the condensate of the air conditioner is measured using a tipping-bucket rain gauge (Fig. 5, #9). Direct evaporation from the soil is minimized by spreading a 2-cm layer of fine gravel on top of the soil. The principle of the system to measure canopy photosynthesis has been described by Louwerse and Eikhoudt (1975). Gas exchange measurements are carried out continually for weeks or even months similar to the technique used by Louwerse et al. (1990) with mobile photosynthesis equipment.

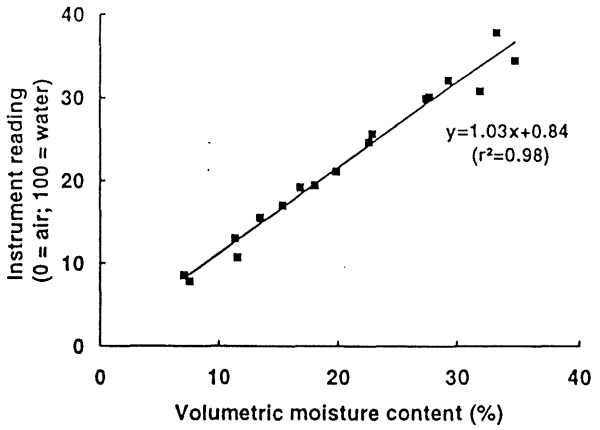

Fig. 7. Calibration curve of capacitance moisture sensors for a sandy soil. Actual volumetric moisture content is determined from the weight difference before and after drying.

Both airflow and CO_2 concentration are also measured at the outlet of the air-drain in the soil (Fig. 5, #13). From the quantity of air passing through the soil and the difference between the CO_2 concentration of the mixed air in the enclosure and that at the outlet of the air-drain (normally approx. 20 $\mu L\ L^{-1}$), the CO_2 production rates in the soil can be calculated separately from the gas exchange rates in the canopy (Van de Geijn et al., 1993).

Computer system

A data-acquisition/control unit (Hewlet Packard HP-300/HP-3852A/HP-3853A) is used to control the technical operation of the facility and to automatically collect the readings from the sensors. The computer controls the sequential switching of valves, processing of signals of the various sensors, automatic calibration, first level data reduction, and periodic transfer of collected data to a central database. It also controls the climatic conditions in the crop enclosures. Reference values for the temperature are taken real time from the weather station.

The readings of the sampling points, with a sampling frequency depending on the time constant of

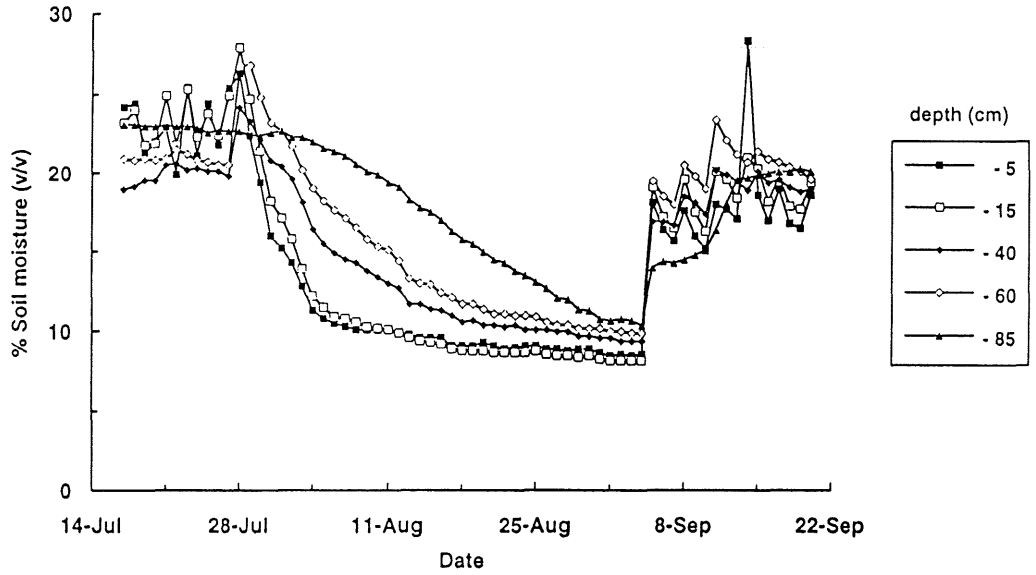

Fig. 8. Soil moisture of a sandy soil grown to Brussels sprouts in various soil layers throughout the season. Points shown are means of the night-hour values, calculated from the 15-minute data. Irrigation has been withheld from end of July till beginning of September. Peaks for the shallow soil layers correspond with irrigation events.

the relevant variable, are stored in a central database. When in full operation, about 1 Mb of data are collected per day.

Minimum experimental data set

The users of the facility are obliged to produce a minimum database on each major experiment. To this end a standard protocol has been developed, describing what samplings and observations must be done, even if the specific aim of the experiment would not require it. This procedure guarantees that datasets are generated which can also be used later for other purposes.

Illustration of some applications

Water extraction at different depths and drought development

An example of the water extraction from different soil layers, calculated from 10-min readings, is given in Figure 8 for a sandy soil planted to Brussels sprouts. Irrigation events are seen as peaks in the volumetric water content of the top 25 cm (lines of −5 and −15 cm). After interruption of the water supply, the top soil layers rapidly dried out, and also at −85 cm the water content dropped within a month to very low values.

After resuming irrigation, the peaks corresponding with water applications were seen again also for deeper soil layers, because of the large water supply (60 mm) given in one operation. Measurements have shown that the system allows to trace quantitatively (+/−10%) the water supplied in each single irrigation operation.

The readings of tensiometers and the water potential characteristics of the soil, determined separately (not shown), when combined with rooting patterns give an almost complete picture of the root-soil processes determining crop performance during long dry spells and after water supply is restored.

Mineral nitrogen uptake from the soil profile

Brussels sprouts were grown in 1990 in the Wageningen Rhizolab on a (repacked) sandy top soil, which was relatively rich in mineral nitrogen. The layer of humous soil was 1 m deep, and was placed on top of a 1-m layer of coarse sand, free of organic matter. Throughout the season, soil solution was extracted at 2-weekly intervals using the microporous tubing elements (RHIZON SSS) (Meijboom and Van Noordwijk, 1992), and analysed for mineral nitrogen content in the laboratory. Using the soil moisture content calculated from the readings of the capacitive sensors, the concentrations were converted to soil mineral nitrogen content. The depletion of the different soil layers is shown in Figure 9.

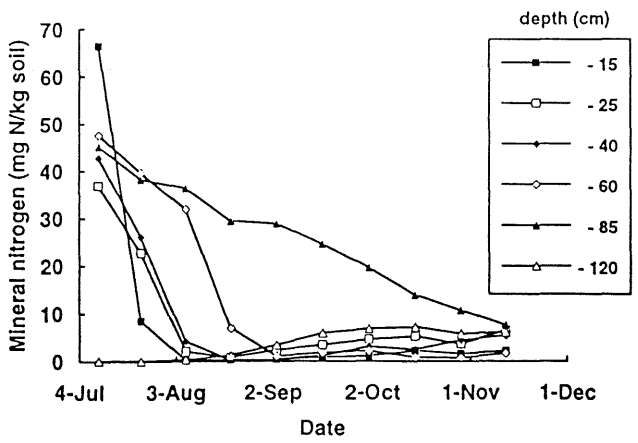

Fig. 9. Development of mineral nitrogen content in different soil layers as determined from soil solution samples extracted by microporous tubing (Eijkelkamp, RHIZON SSS). The sandy soil was grown to Brussels sprouts. Using data on moisture content, solution concentrations have been converted to soil nitrogen content.

Both successive depletion of the soil layers and gradual leaching of mineral nitrogen was detected at −120 cm. Nitrogen depletion curves and water extraction have been related to the dynamics of rooting patterns (root length density), in order to derive values for the root activity. Especially the high uptake after the end of July from the layer at −60 cm was marked. Details of the experiment, including the use of ^{15}N-depleted fertilizer will be published elswhere (Smit et al., pers. commun.).

Gas-exchange measurements

An example of the daily time course of photosynthesis and global radiation intensity is shown for spring wheat in Figure 10. The crop, which had been exposed to elevated CO_2 from sowing onwards, showed a higher net photosynthesis and dark respiration (night period), than the ambient CO_2-treatment. The gas exchange data have also been used to construct a temperature-respiration curve and the carbon balance of the planted soil on a day-to-day basis. It should be realised that differences in photosynthesis and respiration on an area basis may be due to various factors e.g. light interception differences caused by stand characteristics like leaf area index and canopy structure, but also by differences in biomass. However, photosynthesis response curves for CO_2 concentration and effects of temperature and light intensity are normally determined periodically for different stand ages. The combined results may show whether or not adaptation of physiological parameters to imposed growth conditions has taken place.

Relation with actual research questions

The public concern about unintended emissions of nutrients and biocides to the environment thus sets the stage for a search for management techniques and plant cultivars that fully utilise nutrients and other resources, and allow reduction of chemical inputs for plant protection. At the same time it is recognised that little is known about the competition for physical space and nutrients and the turnover of plant roots and how these affect growth and competition in a mixed vegetation (Berendse et al., 1992; McConnaughay and Bazzaz, 1991).

These fields of research may be approached using the facility and technologies as described here to improve the present knowledge. In the Wageningen Rhizolab, limiting conditions in the soil such as nutrient deficiency or depletion, soil compaction, anaerobiosis, and drought can be imposed in a controlled way at a microplot level and thus studied for their effect on various aspects of crop growth and adaptation (crop growth analysis, gas exchange characteristics) and on root development (distribution and turnover during the season). It is important that single specific processes (root growth, water extraction, photosynthesis) can be studied while the overall functioning of the soil-plant system is monitored as well. In combination with computer simulation modelling, this may help to understand better the behaviour of crop systems under environmental constraints.

Since the Wageningen Rhizolab has been in operation (1990), the research has addressed several topics. For example the effects of transient drought stress in interaction with potato cyst nematode infection on crop physiological processes with potato (Haverkort et al., 1994) and the effect of the dynamics and activity of root systems and characteristic rooting patterns of field grown vegetables (leek, Brussels sprouts) on nutrient utilization and interception in different soil layers (Smit et al., 1994b). The effects of CO_2 enrichment (climate change) on photosynthetic acclimation and the daily and season-long over- and underground carbon balance of several arable crops have also been studied (Dijkstra et al., 1993; Van de Geijn et al., 1993).

At present attention is given to the dependence of growth and architecture of the maize root system on soil temperatures in early spring, to better understand the soil nitrogen and phosphorus interception and use. Results of these studies will be published separately.

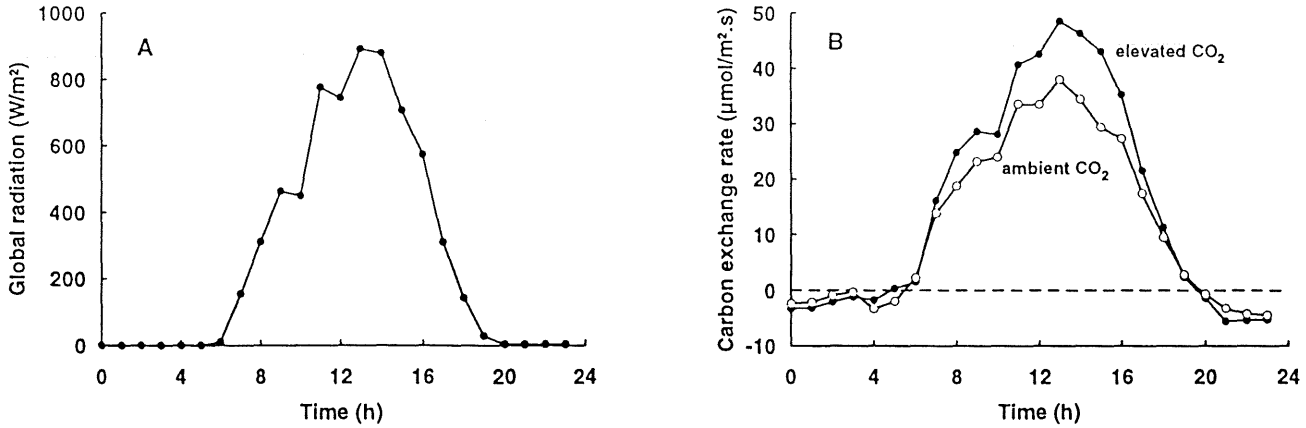

Fig. 10. Global radiation over a day (A) and CO_2 exchange (assimilation and respiration over the same 24 h period), for a wheat canopy grown at ambient (about 350 ppm) and enriched (700 ppm) CO_2 concentrations.

Concluding remarks

A facility such as the Wageningen Rhizolab is a research tool that has to be combined with laboratory and field work. Its value lies in the integral approach, where the results can be used in quantitative mechanistic simulation models. It has been developed to collect information that is relevant for field conditions. Advantages over experiments in field conditions are the possibility to monitor simultaneously several processes, to control conditions (specifically water), and to diminish heterogeneity, thereby improving repeatability.

It has turned out that several studies can be done simultaneously at different scales. For instance, studies of spatial patterns in soil respiration, variations in the CO_2-profile in the soil, temporal variations of root extension rate and decay mostly can be carried out without doing harm to the main (full season) experimental objectives.

The most useful application of the facility lies in the simultaneous study of above-ground crop growth and gas exchange, and detailed underground dynamics of root development, nutrient and water uptake and related soil processes.

A point which is still incompletely resolved is the automatic handling of video images of rooting patterns (Majdi et al., 1992; Smucker et al., 1987). The number of roots per image varies widely, and sometimes roots show little contrast, being almost transparent. Also, one root may show more than one segment in an image. Apart from the technical problems involved in image processing, the advantage of the use of root length along the minirhizotron as compared to the mere number of arrivals of roots to the glass surface is still under debate (Smit et al., 1994a).

In a complex system as described, data collection and retrieval are essential. Like in most automatic data acquisition systems, the constant stream of data generated can easily exceed the investigators ability to process it. A clear a-priori formulation of a scientific question is therefore a prerequisit for extracting efficiently information from the datasets generated.

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