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HYDROLOGICAL RESEARCH IN THE UNITED KINDOM

(Study trip - July 1979)

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C O N T E N T S

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INTRODUCTION

In July 1979, while the authors were on grant from International Agriculture Center, working at the Institute for Land and Water Management Research at Wageningen, a training program was carried out visiting the following experimental stations and institutes in the United Kingdom:

1. Rothamsted Experimental Station (Harpenden, Hertfordshire)
2. Institute of Hydrology (Wallingford, Oxon)
3. Letcombe Laboratory (Wantage, Oxfordshire)
4. Grassland Research Institute (Maidenhead, Berkshire)
5. National Vegetable Research Institute (Wellesbourne, Warwickshire)
6. University of Nottingham, School of Agriculture (Sutton Bonington, Loughborough).

We did be acquainted about several investigations in many fields of research (soil physics - botany - hydrology; mathematical models and instrument téchnology). Unfortunately, the short time available did not allow deepening these subjects. However, some general outlines can be done.

a. First of all, it was very impressive to see the advanced electronics used in measuring all kinds of parameters. This very large diffusion of electronics in the United Kingdom, shows the high level of technology and at the same time, the easy use of these instruments, also if not always so cheap.
   Somebody, joking, said that the massive use of electronics is directly proportional to the well known English dislike against intensive labour ....

b. Secondly, we received a good impression of the new course on research in the United Kingdom in this field, under the supervision and coordination of the Natural Environmental Research Council. The institutes and stations, although spread all over the country, are co-operating, sometimes very strictly, unifying their efforts. The new course is more practical, and strictly related with actual problems of the country. We heard about small computers in the farms, to calculate in real time the nitrogen deficit and so on. This is a present trend and, probably, the way of farming of eighty years.

c. A special relief is being given to deep aquifers recharge, which are very common in the United Kingdom. These aquifers are overlayed by chalk: there are two possible mechanisms for water movement in unsaturated chalk: flow through microfissures and flow through matrix. Investigations are in progress to show the extent to which each of these processes is important for aquifer recharge in chalk, and the physical conditions which control them. This is important for understanding and predicting the long term pollution of chalk aquifers by nitrate. This problem is as important in the United Kingdom as drainage and capillary rise in the Netherlands.

ROTHAMSTED EXPERIMENTAL STATION
HARPENDEN, HERTFORDSHIRE

1. ROTHAMSTED EXPERIMENTAL STATION, grant aided by the British Agricultural Research Council, is the largest and oldest of the British agricultural research centres. Most of the departments are biological, being concerned with the plant in health and disease. Of the non-biological sections, the Physics Department divides its interest between the root environment (soil physics) and leaf environment (agricultural meteorology). In 1979, the ARC Unit of Soil Physics (YOUNGS and TOWNER) moved from Cambridge to Soil Physics in Rothamsted.

2. INVESTIGATIONS IN PROGRESS

2.1. Agricultural meteorology

2.1.1. Irrigations and crop growth.

Between 1964 and 1976,a series of experiments on the heavy silty clay loam, complementary to that carried out between 1951 and 1968 on the light loamy sand at Woburn by H.L. Penman, has been carried out. The Rothamsted and Woburn results have been analysed, for five crops common to both the experiments, to give a comparison of the responses to irrigation on the two soils. These responses were measured in terms of limiting soil moisture deficit D_l (which is the deficit that must be exceeded before any additional plant growth will result from irrigation) and in terms of the incremental gain, k, in crop yield per unit of applied water.

In Rothamsted experiments, irrigation was applied through oscillating spraylines, and the schedule for fully-irrigated treatments sought to maintain below 30 mm the calculated potential moisture deficit. Other treatments received no irrigation or, in some years, partial irrigation, when full irrigation was applied for only the first, or the second, half of the growing season.

Table 1. Comparison between Woburn and Rothamsted experiment results

Crop	D_1 (mm)		k (t ha^{-1} mm^{-1})	
	a	b	a	b
1. Beans	< 30	80	0.006	0.014
2. Potatoes	35	85	0.20	0.19
3. Spring barley	40	100	-	-

a = light loamy sand (Woburn)

b = silty clay loam (Rothamsted)

In none of these researches were the plants short of water during germination and emergence processes that are particularly sensitive to soil water content. The comparison, in the irrigation experiments, of the effects of water deficits in the first and second halves of the growing season suggested that beans and barley were slightly more sensitive to early than to late deficits, probably because the roots exploited a lesser depth of soil in the early period.

2.1.2. Analysis of micrometeorological records.

The objective of these analyses is to determine values for the roughness length, z_o, the zero plane displacement, d, and the drag coefficient, c_d.

Micrometeorological analysis has been concentrated on the data that were collected for beans, potatoes and spring barley, restricting calculations to data gathered when the atmosphere was at or close to the neutral thermal stability. To support these analyses, new computer programs, drawing on the GENSTAT package, have been developed. Differences between the parameters derived for each season's north and south plots, irrigated and not irrigated, give an indication of the effects of water stress on aerodynamic properties.

2.2. Plant physics

2.2.1. Water stress and crop growth

Shortage of water restricts crop productivity all over the world, not just in arid or semi-arid areas: in any area where the evaporative demand greatly exceeds rainfall during the growing season, water stress, resulting from the withholding of water supply, leads directly to changes in the physical environment of the crops and thus in the crop physiology. Moreover, as the soil is dried, the soil water potential decreases and so does the soil hydraulic conductivity. Thus it is more difficult for plants to extract water, the plant water potential tends to decrease with loss of turgor and wilting of leaves. The consequence is a reduction of light interception and photosynthesis rates.

At Rothamsted station the crop response to water stress is being investigated on a field site that was protected from rain by automatic shelters. Irrigation was applied to individual plots on a predetermined schedule to give a wide range of treatment from 'weekly irrigation' to 'no irrigation' from emergence to harvest.

Relating the response of the crop to the applied water stress gave information both on stress-sensitive aspects of development and on how yield was affected. A linear relationship between the grain yield of each treatment and the water used, covers all treatments used (fig. 1).

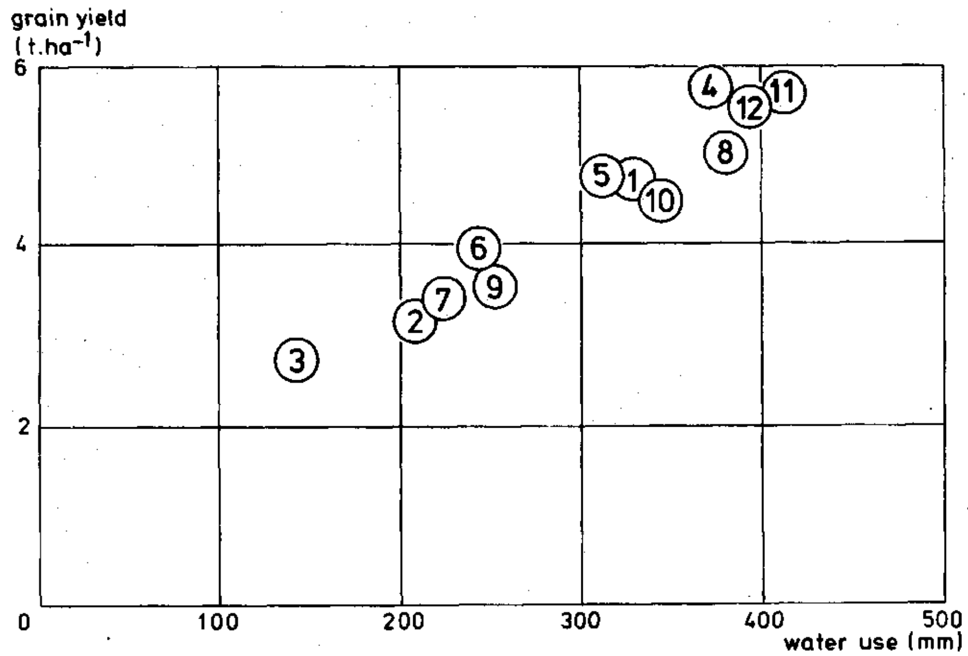

Fig. 1. Grain yield versus water use for 12 different treatments of water stress (after W. DAY, Water stress and crop growth, 1978)

2.2.2. Plant response to water stress

The effects on barley yield of droughts of various intensities at different growth stages were investigated. Analysis of the yield and growth measurements has sought to determine how much of the drought-induced yield loss can be ascribed

1. to a reduction in leaf area
2. to increased stomatal resistance
3. to a decrease in individual leaf photosynthesis
4. to an increase in respiratory losses

A model for the total yield, Y, of dry matter (grain, straw, roots) at harvest is proposed

$$Y = I * P/I * F$$

where

I = total amount of visible radiation intercepted by green foliage

P/I = variable proportional to the efficiency of use of the intercepted radiation

F = proportion of total photosynthate that remains at harvest, not lost to respiration

Measurements showed that drought-stressed plants intercepted less radiation than unstressed ones because they had less total leaf area and because they matured earlier; also, there may have been a change in the angle of foliage in stressed plants, allowing more radiation to pass between their leaves without interception. The effects of drought on the ratio P/I were mainly, but not entirely, through differences in stomatal closure. Effects of changes in individual leaf photosynthesis were not detected: the measurements of internal resistance to carbon dioxide transfer, r_c, and of leaf quantum efficiency, ε, were of insufficient precision.

Through the model, which predicted the measured yield losses reasonably well, the interpretation of the drought experiment is that, at any time in the season, if drought reduces yield it does so mainly by causing a reduction in I: for plants droughted from emergence to harvest, the reduction, in comparison to fully watered plants, was 40%.

2.2.3. Photosynthesis

In field, measurements were made on six small plots of spring barley. Out of them after emergence, two were sheltered from rain, two exposed to rain, and two exposed to rain and irrigated. Stomatal resistances to water vapour transport were measured with the continuous flow porometer and also with a portable leaf chamber that can simultaneously measure photosynthesis and stomatal resistance. The data collected are being used to test mathematical models and develop computer programs.

By laboratory experiments on wheat and barley plants they have sought (in constant environment chambers) to measure the effects of temperature on parameters of the photosynthesis model prepared in 1977.

2.2.4. Continuous flow porometer

The instrument has been compared with two different diffusion porometers through laboratory calibrations and through measurements on growing leaves in field and glasshouses. The analyses of comparison are still proceeding.

2.3. Soil physics

2.3.1. Soil water

2.3.1.1. Soil water movement in heterogeneous soils. Real soils are often non-uniform and the development of water profiles will be affected by any non-uniformity. Under controlled experimental conditions, the development of water profiles has been observed in columns filled in two layers, by two materials with pores of different size, but similar shape. Various initial and boundary conditions were imposed upon the columns and their influences investigated, the hysteretic properties of the wetting and drying processes having previously been determined on the same columns. In a representation of this system that gives rise to equations that are more readily solvable, the depths of the layers and the times of duration of flow are scaled according to similarity principles so that the corresponding scaled hydraulic properties are identical in the two layers - and a source term can then be imagined to act at the layer boundary. The use of scaling techniques is being further exploited by inclining the columns; their effective length is thereby increased, reducing the effect of gravity, and measurements can consequently be made with greater precision.

2.3.1.2. S o i l   w a t e r   m o v e m e n t   i n   s w e l l i n g   s o i l s. Real soils are heterogeneous; in addition many are prone to swell as they wet up. The basic laws of soil water movement relate to non-swelling soils and any swelling soil generalisations of these laws must allow for two important and complicating factors. First, Darcy's law that relates velocity of waterflow to the gradient of hydraulic potential refers that velocity to the moving soil particles, rather than to a fixed coordinate. Second, the equilibrium water content in any elemental volume of soils depends not only on the pressure in the soil water, but also on any mechanical forces that may be exerted on the soil matrix.

In preparation for experimental studies of the combined effects of water pressure and mechanical loading on the water content of dry soils, a triaxial shear test apparatus is currently being tested and calibrated and, in addition, a new design of hydraulic conductivity cell has been conceived, and a prototype apparatus is being set up. This cell will be used to examine the hydrodynamics of one dimensional steady flow in constrained, saturated, swelling soils. A particular feature of the cell is its facility to permit separate segments of the clay column to be rapidly isolated and sealed in readiness for subsequent determinations of water contents.

2.3.1.3. H y d r o d y n a m i c   d i s p e r s i o n. The dispersion of soil water solutes crossing an interface between two regions of uniform but different pore sizes has been simulated in a one-dimensional laboratory experiment. The interface, in a horizontal column, was between glass heads of two diameters through which water and the solute, a dye, could be caused to flow. From an analysis of the dye concentration profiles along the column it is possible to calculate the conditions of continuity for the flux and concentration at the interface.

2.3.1.4. Hydraulic conductivity measurements. The variations with depth of hydraulic conductivity is useful to know in any applications of theory to the design of drainage schemes for heterogeneous soils. In a uniform soil, the hydraulic conductivity can be determined from the rate of inflow of water to an augered hole, and this method has been modified to make it suitable for layered soils. To furnish the supporting theory, a new exact method has been developed by Youngs to calculate the initial rate of flow to a ditch from a level water table when the ditch water level is suddenly lowered; and this method has been adapted for analysis of radial flow to an augered hole. This theory must now be extended to allow for variations of hydraulic conductivity.

2.3.2. Soil structure

Investigations are in progress about gaseous diffusion in compacted soils, because, at field capacity, tilled soils may be easily compacted with probable detriment to the diffusion through them of oxygen and carbon dioxide. In a laboratory experiment, measurements have been made of the effects on gaseous diffusion coefficients of the various degrees of compaction: at field capacity, when the pores within the crumbs are saturated and those between the crumbs are drained, the effect of a sudden compression of a bed of crumbs is to subject each crumb to a plastic deformation, in which the shape, but not the volume, changes, and to decrease the total volume of the bed. This loss of total volume is almost entirely related to the loss of those intercrumb pores that are essential if gases have to diffuse through the bed.

Another experiment in progress is a tillage experiment sought to determine whether tillage treatments and the soil water content in the 0-30 cm layer at the time of tillage, caused or promoted measurable changes in the physical properties of the soil and whether these changes could, in turn, be related to crop growth and yield.

INSTITUTE OF HYDROLOGY
WALLINGFORD, OXON

1. THE INSTITUTE OF HYDROLOGY is a component body of the National Environment Research Council. It is responsible for a programme of basic research into all the aspects of hydrology and also undertakes projects of an applied nature in Britain and abroad. The Institute's research programme is divided into some 30 projects (Hydrological systems; Mathematical modelling of catchment systems; Water resources studies, etc.).

2. INVESTIGATIONS IN PROGRESS

2.1. Unsaturated soil water flow

2.1.1. Water and nitrate fluxes in unsaturated chalk

In 1972 an experiment was set up at Bridgets Experimental Husbandry farm to investigate the effect of inorganic fertilizer and animal waste slurry applications to grassland on the nitrate nitrogen content of the interstitial water in the unsaturated zone of the chalk. The Institute of Hydrology participates in the experiment, particularly to investigate the water fluxes in the chalk needed to quantify nitrate flux. The experiment is relevant to two areas of concern

a) the possible long-term pollution of the chalk aquifer by nitrate agricultural origin
b) the efficiency of applied nitrogen fertilizers

A further application is in clarifying the mechanisms of water and solute movement in unsaturated chalk.

Water fluxes are calculated using simultaneous measurements of water content and tension to 3 m. depth in chalk throughout the year. During the winter, drainage has been estimated from a water balance, assuming runoff negligible

$$D = R - E - \Delta M$$

where

D = drainage

R = rainfall

E = evaporation (Penman E_t)

ΔM = change in soil moisture content

During the summer, the Zero Flux Plane method has been used to partition water fluxes into evaporation and drainage, identifying the depth, at which the potential gradient - and hence the flux - is zero, by mercury manometer tensiometers, calibrated gypsum resistance blocks and pressure transducer tensiometers.

Interstitial water was sampled by in situ ceramic cup suction samplers and the water was analysed for nitrate nitrogen by ADAS. The soil of the experimental site is an Andover series with approximately 0.3 m. of silty loam horizon overlying the chalk which was in a comparatively fresh and seemingly undisturbed condition. The seasonal changes in the unsaturated fluxes and their upward and downward partition by the Zero Flux Plane is shown in fig. 2.

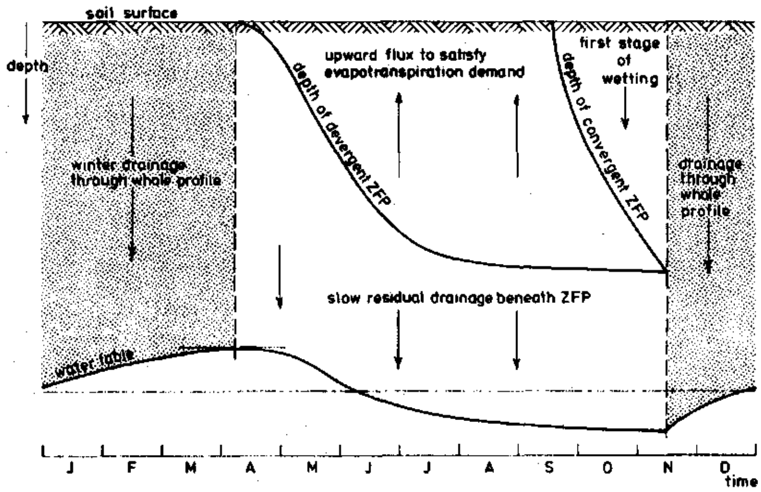

Fig. 2. Seasonal partition of water fluxes by the Zero Flux Plane in the unsaturated zone of the chalk

Fig. 3. illustrates the drying and re-wetting sequences and the movement of the zero flux planes. The results obtained suggest that nitrate in solution would have been moving upwards to the root zone of the plants for a substantial period during the summer and from substantial depths. The implications of this upward flux of nitrate are not yet clear.

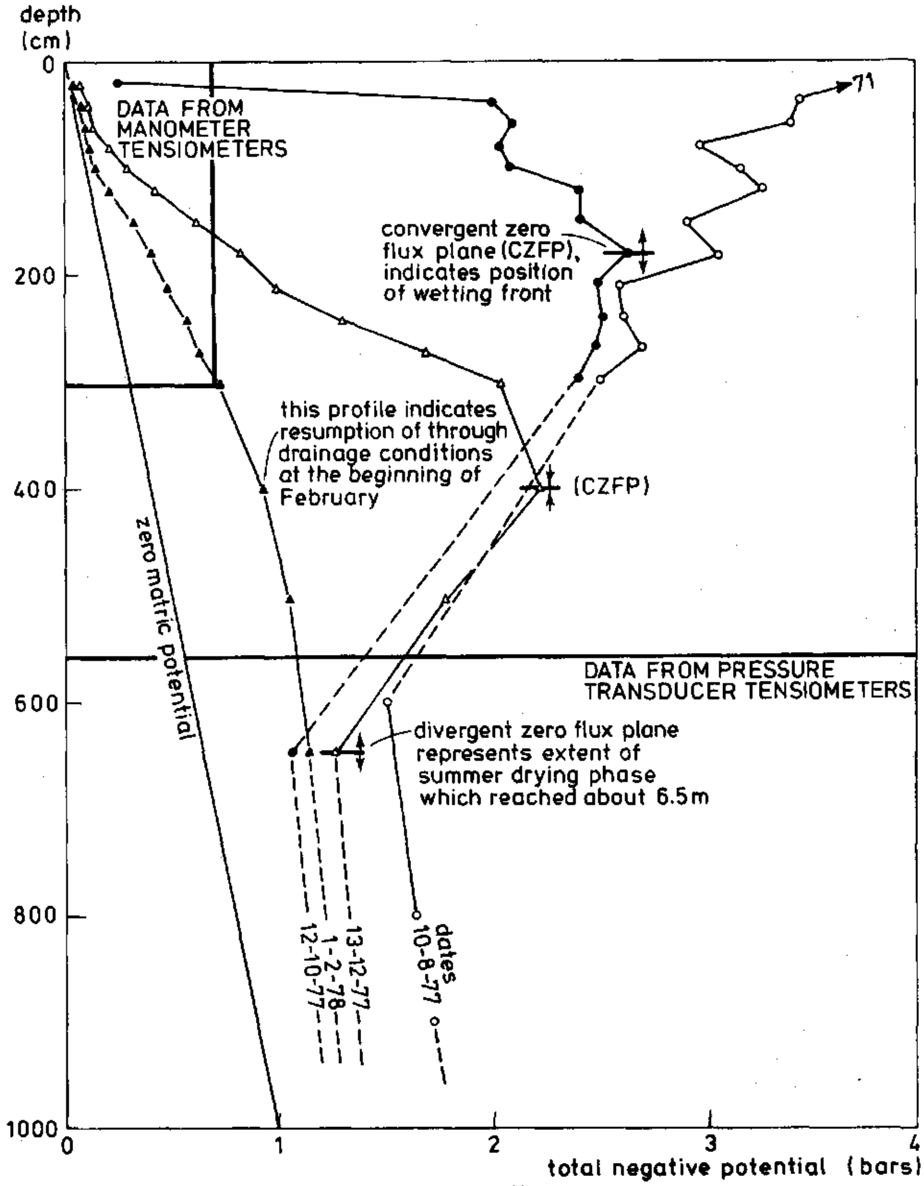

Fig. 3. Total potential profiles from gypsum blocks, pressure transducer and mercury manometer tensiometers, Bridgets EHF 1977-78

2.1.2. Groundwater recharge, soil physical methods

Usually the evaluation of aquifer recharge is obtained from the difference between rainfall and an estimate of evaporation based on Pe man's equation. The value of both these parameters is of the same order of magnitude, so that aquifer recharge estimates may be affected by large errors. The investigation is in progress to measure downward fluxes directly, using soil physical methods.

Results will be compared with those derived from the nearby undisturbed five cubic meters lysimeter and also with the standard meteorological methods.

Fig.4 illustrates the plan of the Fleam Dyke experimental site, where two plots are instrumented, each one by four access tubes (3.3 ÷ 12 m. deep) to allow measurements of the soil moisture content profile of the chalk using a neutron probe. Two sets of mercury manometer tensiometers are also operating on each site to provide soil moisture potential profiles to a depth of 3.0 m. Finally on the edge of each plot there is a 35 m. deep, 150 mm. diameter borehole (intersecting the water table at a depth of 20 m) into which are inserted pressure transducer tensiometers recording in digital form on tape cassettes. An automatic weather station and raingauge are situated nearby for comparison of results with recharge calculated from meteorological information.

The lysimeter has three 5 m. deep neutron probe access tubes and a set of five purgeable pressure transducer tensiometers at depths between 1 and 4.5 m.

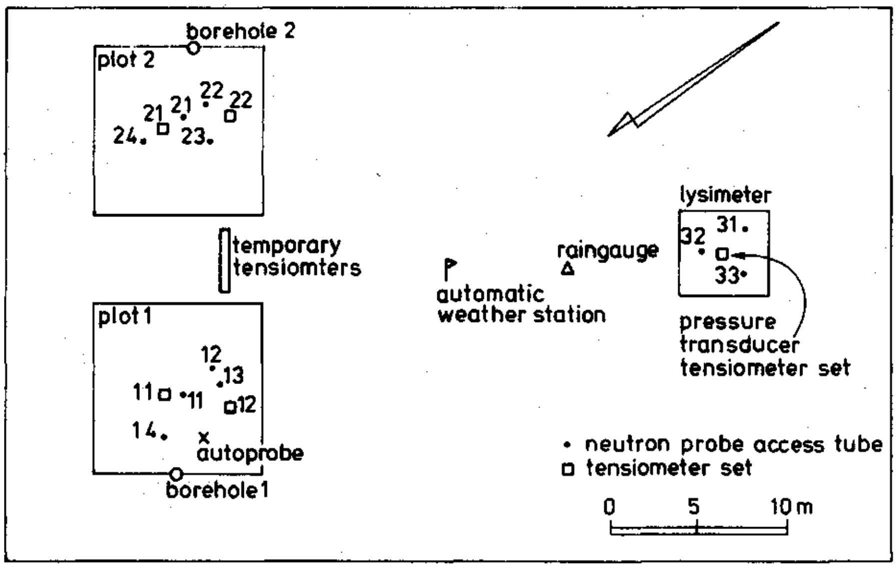

Fig. 4. Plan of the Fleam Dyke experimental site

LETCOMBE LABORATORY

WANTAGE

1. THE LETCOMBE LABORATORY is concerned with the growth of crops in relation to soil conditions, including drainage, and the longterm influence of different methods of cultivation on soil structure and fertility The influence of transient waterlogging on crop growth is studied; lysimeters containing undisturbed columns of soil are installed in a substructure so that their surfaces are level with the surrounding soil which carries a guard crop. A mobile glasshouse with a traversing irrigation system allows a predetermined rainfall pattern to be simulated. Tunnels under the guard crop give access to the lysimeters for regulation of watertables, collection of drainage water, sampling the soil water and atmosphere and monitoring soil temperature. Variations in moisture profiles are measured with a neutron probe. Nitrogen 15 is being used as a tracer to study the utilization of nitrogen fertilizer by the crop, and leaching through soil. In the laboratory studies are in progress on the size and continuity of soil pores in relation to the movement of both water and gases. A small investigation is in progress into the relative movement of tritium-labelled water and nitrate down columns of undisturbed chalk: this is relevant for studies of the leaching of fertilizers into aquifers.

2. INVESTIGATIONS IN PROGRESS

After investigations on the absorption of nutrients and water by roots, with particular emphasis on the contrasts between different parts of the root system, investigations are in progress on the factors, such as variations in temperature and nutrient availability, which modify root growth and function, to reach a better understanding of the behaviour of crop plants when exposed to stresses in the field.

2.1. The physiology of root growth and function

2.1.1. Effects of variations in transpiration rate and water potential on uptake and loss of water

It was observed that in solution culture, substantial quantities of labelled water which have been supplied to segments of roots of young barley plants, were released by older portions of the root systems. This loss of labelled water was necessarily accompanied by exchange with unlabelled water and its magnitude appeared to be positively correlated with the rate of transpiration by shoots. At the Letcombe Laboratory, experiments are now in progress in sand culture to investigate the influence of variations in the rate of transpiration and of differences in water potential between shoots and roots. Attention is given to the possible effect of gradients of water potential on root resistance. Barley seedlings are grown in coarse sand in a perspex cylinder, divided into two compartments by horizontal wax membranes, supplied by deuterium oxide (DHO) the upper one, where the old roots are, and by tritiaded water (THO), the lower, where the young roots are. Concentrations of deuterium and tritium in the transpirate,shoots and the two compartments are determined by mass-spectrometry and liquid scintillation counting respectively. Leaf water potentials are measured by the pressure-bomb method. Transpiration rate is varied by illuminating the plants for a 16-hour day, as in the growth period, or by maintaining them in the dark.

Results refer to:

a) effects of transpiration rate and ambient water potential on uptake and loss. The total labelled water transported to the shoots and transpiratedby plants in the light is about four times that by plants in the dark, which have much higher leaf water potentials (as shown in fig. 5).

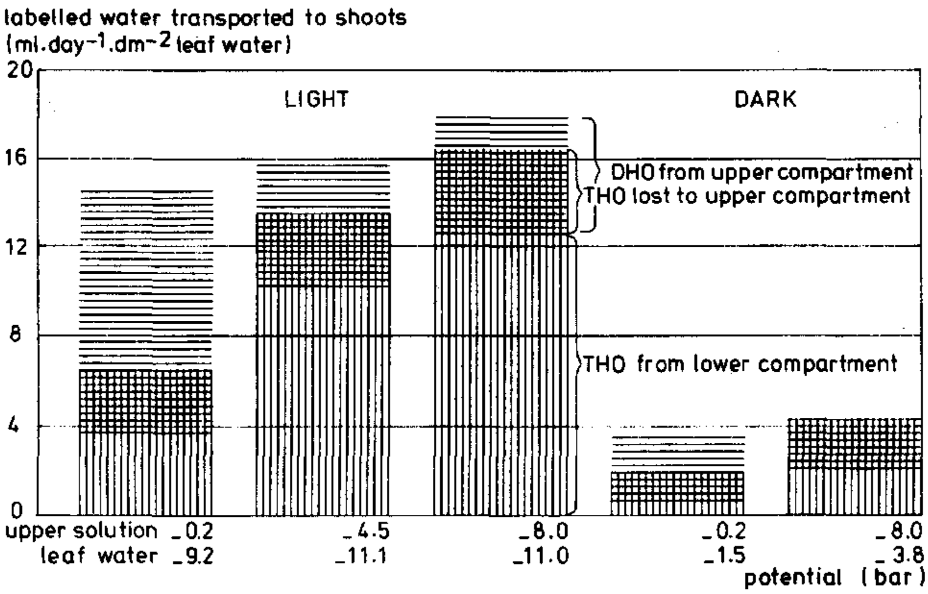

Fig. 5. Effects of light and dark, and of variations in water potential of solutions surrounding barley roots, on transport of labelled water from roots to shoots and transpirate. Effects on leaf water potential are also shown

As results from fig. 5, lowering the potential of the solution in the upper compartment has brought about a small increase in the total water transported in both light and dark, but a considerable reduction in the proportion of DHO. According with the results discussed above, part of THO transferred from the lower to the upper compartment, is released and substituted by DHO. Loss of THO is significantly greater at the higher transpiration rate, despite the greater uptake of water from the upper compartment which would bring about increased reabsorption of any THO lost by the roots. Lowering the water potential, however, has little effect on the magnitude of the loss of THO. This result suggests that the pathways of movement into, and out of, the roots were different.

Longitudinal diffusion in the cortex and subsequent exchange could provide an alternative pathway for loss of THO, depending on the relative rates of movement in this time and bulk mass flow in the xylem. Theoretical considerations and experimental evidence however, suggest that longitudinal bulk flow of water in the cortex does not occur to any great extent.

At -8.0 bar in the dark, outflow of THO into the upper compartment is approximately equal to inflow. This effect can be attributed to a lowering of the root resistance with increasing pressure applied to the roots and a comparable mechanism might contribute to the apparently greater loss of THO at high transpiration.

b) Effects of transpiration rate and water potential on root resistance. The difference in water potential, $\Delta\Psi$, between the leaves and the solution surrounding the root segments in the two compartments was taken as

$$-(\Psi_1 - \Psi_s)$$

where

Ψ_1 = leaf water potential

Ψ_s = osmotic potential of solutions

Fig. 6 shows the relationship between $\Delta\Psi$ and the net uptake from the two compartments: the apparent resistance of the root, as given by the slope of the curves in that figure, declines with increasing $\Delta\Psi$ and transport of water across the root. Net uptake of water appeared to continue even when the osmatic potential of the medium in the upper compartment was lower than the leaf water potential ($\Delta\Psi<0$).

Since both compartments contained lateral roots, no conclusion can be drawn on the extent to which transpiration rate were affected by the physiological age of the main axis.

The net uptake by roots from the upper compartment was taken as the difference between the DHO transported to the shoots and transpirate and the THO lost to the upper compartment. Measurements of net uptake carried out by potometers support the estimates derived from tracer movement.

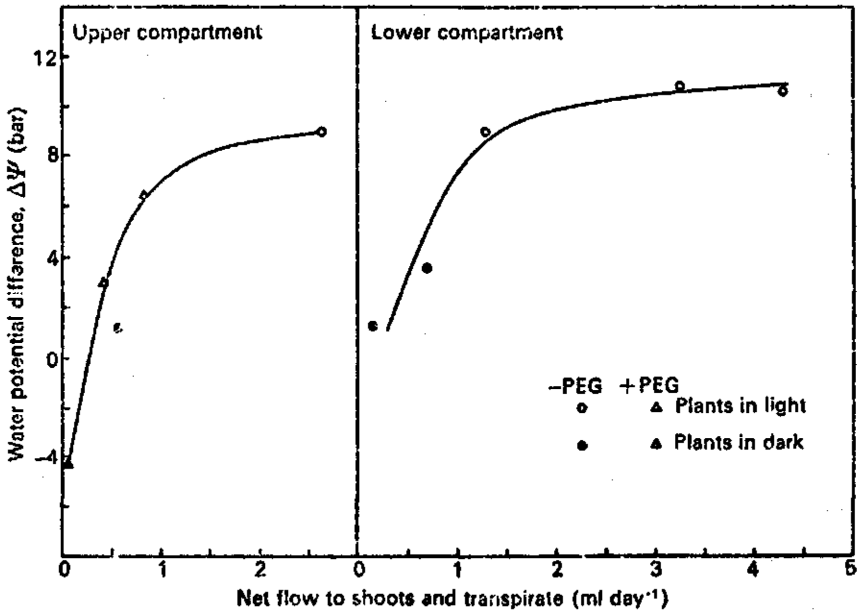

Fig. 6. Relationship between the difference in water potential (ΔΨ) of leaves and of solution surrounding roots, and the net quantity of water transported from two compartments to shoots and transpirate over one day

2.1.2. Permeability studies on the epidermal/hypodermal layers

The anatomical structure of roots in regulating the absorbtion of nutrients and flow of water is studied, because, as roots age, progressive development of the endodermis and, in some species, the hypodermis, may modify resistance to flow of solutes and water. Autoradiography and electron microscopy are used. Conflicting results raised the question of which developmental features are crucial in determining the permeability of hypodermal cell walls.

In mais (Zea mays) the deposition of suberin lamellae in hypodermal walls is accompanied by a marked decline in the radial movement of phosphate across the root.

In the roots of onion (Allium) suberin lamellae appear in the outermost ranks of cortical cells at relatively short distances (<10 cm) from the root apex. The decrease in the permeability of intact roots when the hypodermis suberizes is not so evident, and sleeves of isolated epidermal/hypodermal cells have relatively high permeability to water, ions and small organic solutes.

In sand sedge (carex arenaria) the outer two or three ranks of cortical cells develop thick walls without intercellular spaces at a distance of 1-2 cm from the apex of rapidly extending adventitious roots. At a distance of 3 cm suberin lamellae are seen in the hypodermal walls, while at greater distances (5-8 cm) large numbers of inner cortical cells degenerate. The results show that there is a large decrease in the radial movement of labelled phosphate and potassium ions across the cortex at distances more than 3 cm from the root apex.

Removal of the epidermal/hypodermal layer at 11 cm from the apex by microsurgical technique increased the movement of ions into xylem to a rate comparable with that at 1 cm from the apex.

Experiments with intact roots lead to the conclusion that epidermal/hypodermal walls are very impermeable to ions once they are suberized.

2.2. Response of plants to waterlogging and anaerobic soil conditions

Investigations are in progress to obtain a better knowledge of the factors responsible for waterlogging damage in crop plants.

2.2.1. Effects of waterlogging on crop growth and nutrient uptake

Nodal roots have been observed to grow into waterlogged soil where anaerobic conditions can severely inhibit nutrient uptake and the growth of seminal roots. Nodal roots were able to grow to a depth of about 20 cm in the anaerobic soil.

Plants were grown in aerated nutrient solution at 14°C in a controlled environment room for 13 days. Half the culture were then subjected to a low concentration of oxygen by flushing the solution continuously with nitrogen gas; the remaining cultures (controls) were fully aerated.

Deoxygenation of the nutrient solution gives the same responses as plants grown in waterlogged soil, such as:

. marked retardation of the growth of shoots and seminal roots
. early senescence of the lower leaves, due to the transport of nitrogen out of the older leaves to the younger ones, in which the growth continues
. higher percentage of dry matter in the shoot
. decreasing in Nitrogen transported to the shoots (1.14 mg in non aerated solutions and 16.64 mg in aerated ones, during the same period).

Experiments to test the ability of nodal roots to absorb ions under conditions of low oxygen supply, after the seminal roots have been removed and the cut ends being coated with silicone grease, show (table 2) that

. the transport to the shoots of N^{15}-labelled nitrate by intact roots was reduced in plants grown in deoxygenated solution (treatment 3 compared with treatment 1), although this was partly relieved by aeration during the uptake period (treatment 5 compared with treatment 3)
. uptake by nodal roots alone was severely restricted in plants grown in deoxygenated solution (treatment 4 compared with treatment 2) and was non alleviated by aeration during the uptake period (treatment 6).

Poor shoot growth will reduce the demand for nutrient from the roots, and may account for the lower rates of uptake of nitrate and phosphate in treatments 3 to 6. However, when oxygen has been re-introduced to the intact root system (treatment 5), an increased transport of nutrients occurs, which does not occur with the nodal roots alone (treatment 6).

Experiments ou growth and nutrient uptake in wheat in sandy soil in anaerobic condition were performed. The concentration of oxygen in the soil solution fell to less than 1% within 24 hours of the start of waterlogging. It was observed that the transport of all the nutrients to shoots was reduced within 2 days of waterlogging, presumably in

Treatment number	Gas treatment		Seminal roots	Dry weight (mg)		Transport of ^{15}N-labelled nitrate to shoots in 24 hours (mg)		
	Treatment period	Uptake period		Seminal roots	Nodal roots	per shoot	per g intact root	per g nodal root
1	Air	Air	Intact	222·5	35·8	3·45	13·1	—
2	Air	Air	Removed	—	54·4	0·29	—	5·5
3	Nitrogen	Nitrogen	Intact	27·9	22·9	0·07	1·4	—
4	Nitrogen	Nitrogen	Removed	—	30·8	0·04	—	1·3
5	Nitrogen	Air	Intact	23·1	19·2	0·14	3·5	—
6	Nitrogen	Air	Removed	—	27·3	0·03	—	1·1

response to a lack of oxygen around the roots. After the teme adapted (aeranchymatous) nodal roots grew into the anaerobic soil, allowing the transport of nutrients to the shoots.

As resulting from fig. 7, transport of nitrogen, phosphate and potassium remains depressed, despite the relatively high concentrations of theseions in the soil solution. The amount of calcium in shoots was less affected and increased continuously throughout the period of observations.

It is important also to examine whether inhibition of nitrogen uptake into plants during waterlogging could be attributed to

. the reduced ability of the nodal roots to absorb nutrients;
. the smaller root system, due to death of seminal roots;
. the lowering of the concentration of nitrate in the soil by microbiological activity.

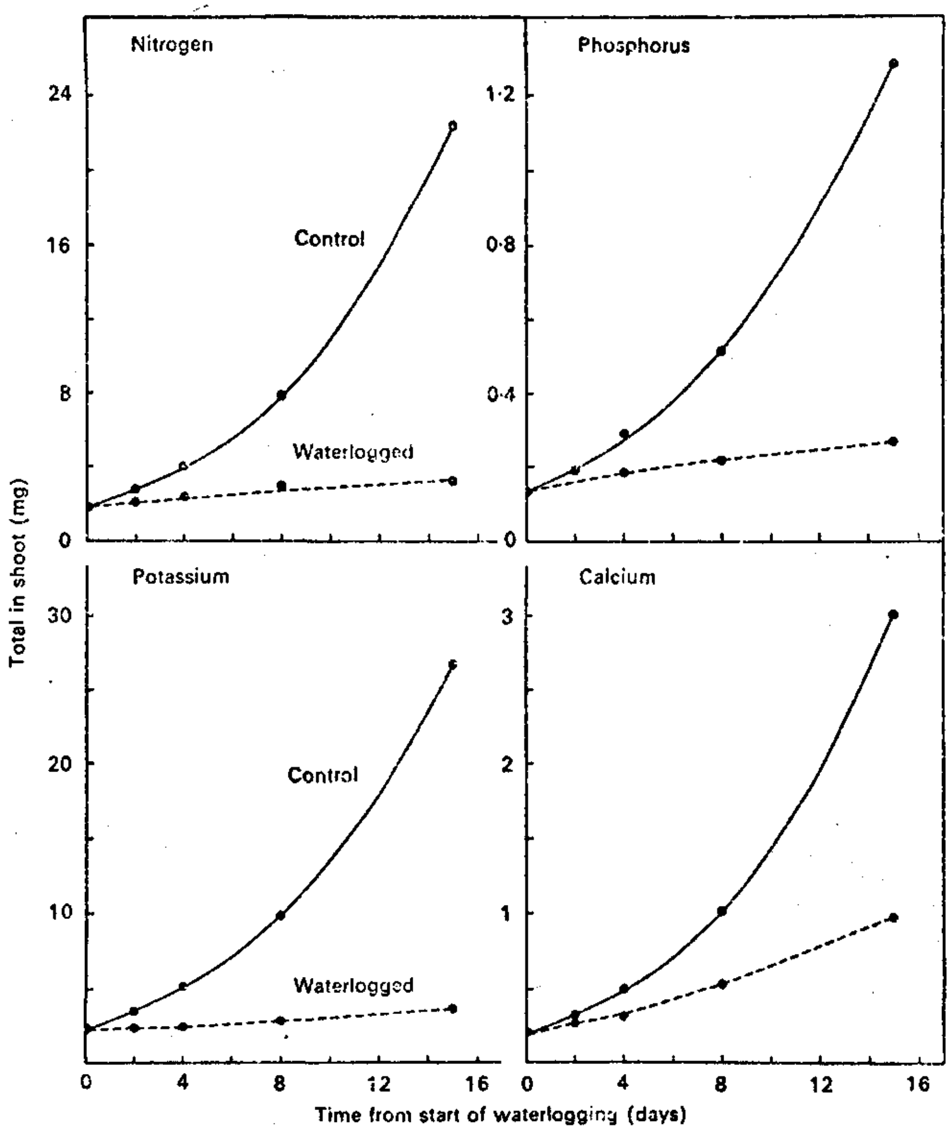

Fig. 7. Influence of waterlogging on the total content of nutrients in the shoots of winter wheat

Due to the waterlogging, the growth of seminal roots of wheat was severely inhibited, but nodal roots were able to grow to a depth of about 20 cm in the anaerobic soil. The rate of increase in the fresh weight of shoots was reduced after only a 2-day waterlogging, net dry weight increased more rapidly than control plants for the first 4 days. In consequence there was a rapid increase in the percentage of dry matter in the shoots: this may reflect an accumulation of photosynthate in the shoot as a result of inhibition of translocation to the root.

Time from start of waterlogging (days)	*0*	*2*	*4*	*8*	*15*
Total shoot					
Dry weight (mg)					
Control	42·5	67·2	97·4	229·8	791·5
Waterlogged		72·4	120·4	221·9	364·2
Fresh weight (mg)					
Control	305	460	625	1439	4338
Waterlogged		411	560	934	1432
Percentage dry matter					
Control	13·9	14·6	15·6	16·0	18·2
Waterlogged		17·6	21·5	23·8	25·4
Seminal root dry weight (mg)					
Control	25·8	39·5	57·4	112·3	382·8
Waterlogged		25·7	29·4	28·2	41·0
Nodal root dry weight (mg)					
Control	—	1·6	4·7	20·3	117·8
Waterlogged		1·1	4·3	18·8	53·6
Length of longest nodal root (cm)					
Control	—	5·5	11·8	26·2	35·1
Waterlogged		3·0	6·8	14·2	19·5

2.2.2. Lysimeter studies on the effects of short-term waterlogging on crop growth

A monolith lysimeter system has been designed to expose crops to predetermined waterlogging events (fig. 8,9 and 10). The installation allows crops to be grown in an environment which is as close as possible to that in the field except the drainage and rainfall (both natural and artificial) which are controlled.

Quantitative information on the response of crops to transient high water-tables will allow to design more efficient field drainage systems.

The yield of peas is significantly reduced by quite short periods of waterlogging (e.g. 8 days) late in the vegetative growth, but even prolonged waterlogging in winter had only a small effect on the yield

Fig. 8. The substructure containing lysimeters with undisturbed columns of soil. Variations in soil moisture profiles are measured with neutron probes

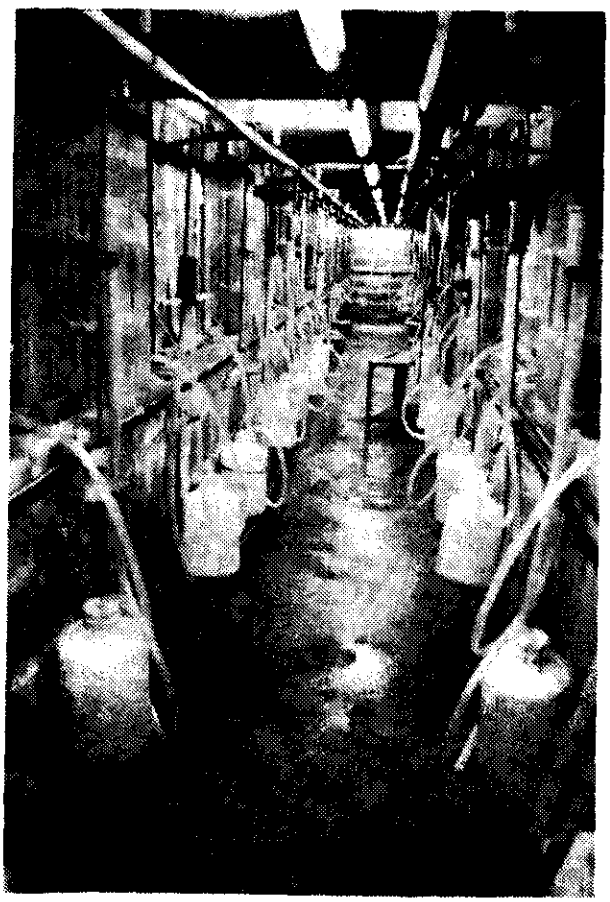

Fig. 9. Detail of the tunnel for regulation of water tables, collection of drainage water, sampling the soil and monitoring soil temperature

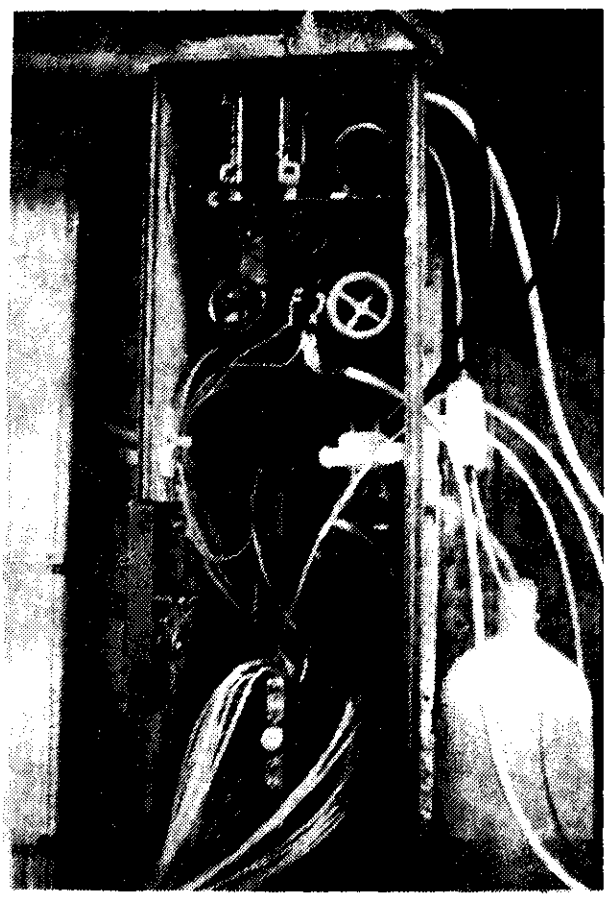

Fig. 10. Detail of automatic apparatus of recording moisture content, suctions and water table adjustment at the required level

of oil seed rape; this crop shows a considerable capacity for compensatory vegetative growth. Waterlogging

as long as 80 days during winter reduced yield of winter wheat by only 16 per cent. Probably, a development of aeranchyma in nodal roots may contribute to the survival of this crop provided that its foliage is not submerged.

Two investigations on the influence of the supply of nitrogen to plants on their response to waterlogging showed that:

1. when the whole root system is in anaerobic environment, the application of nitrogen does not mitigate the effects of water logging on shoot growth.
2. under anaerobic conditions nitrate does not serve as an electron acceptor, as an alternative to oxygen in the respiration of roots.

However, the nitrogen status of plants can have a considerable effect, injury being much reduced if plants contain abundant supplies of nitrogen at the onset of waterlogging.

2.3. Effects of cultivation on soil physical conditions

Some observations show considerable differences in the water regimes on ploughed and direct-drilled soil. Fig.11 shows water profiles at the time of harvest in 1976 compared with those in early November, when soil water content had increased considerably, and in mid-February when it was maximal. In November there were only small differences between the two cultivation treatments above 60 cm but from there down to about 150 cm the direct drilled soil held more water. Later,when the water content of the whole profile had increased, the direct-drilled soil was above 20 cm but the reverse occurred between 20 and 70 cm.

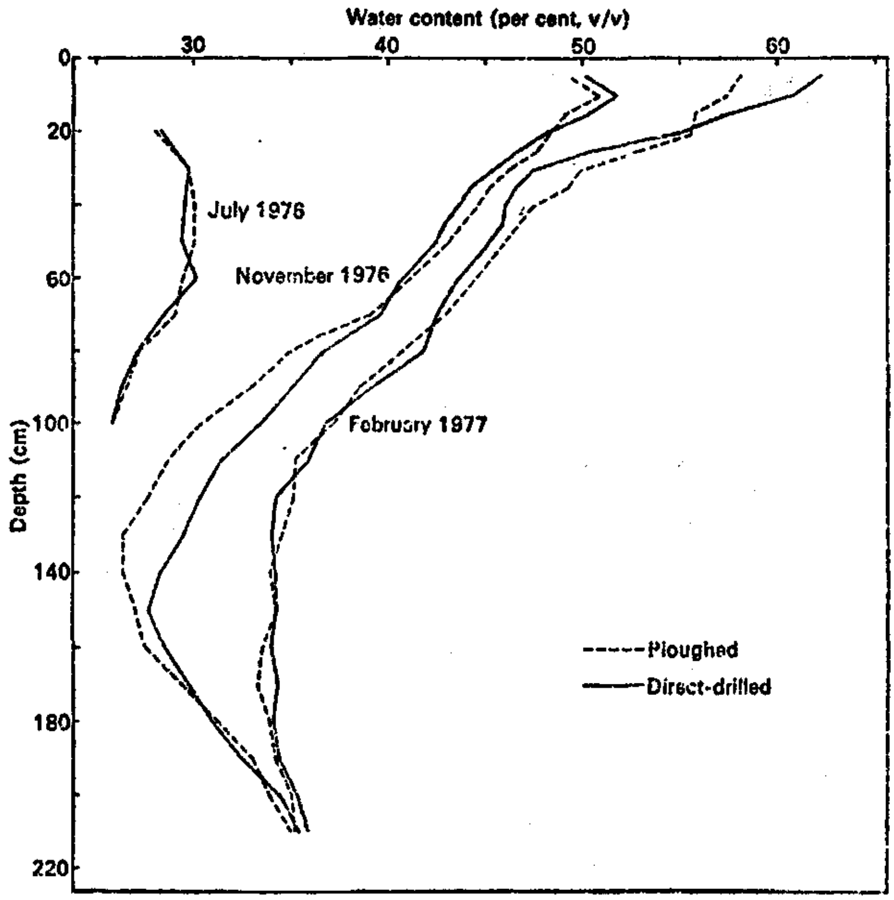

Fig. 11. Water content at different depths in direct-drilled and ploughed soil (Denchworth series) on three occasions in 1976-77

Previous results indicate that the downward movement of water can be more rapid after direct drilling, possibly due to greater continuity of pores and planes of weakness.

In fig. 12 are shown results obtained collecting samples from the upper 30 cm of soil and measuring water content at the time of collection and after they had been equilibrated for seven days at a potential of -60 cm of water.

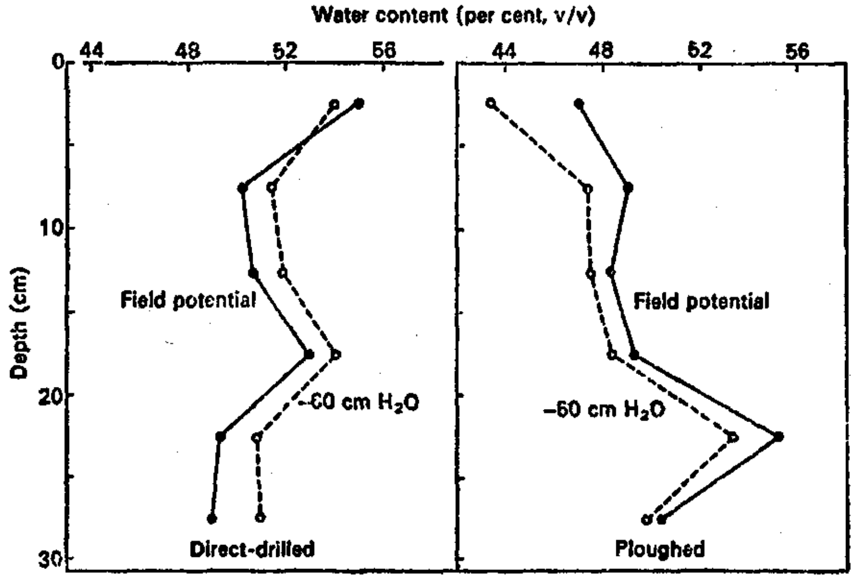

Fig. 12 Water content in the top 30 cm of direct-drilled and ploughed soil (Denchworth series) at the time of collection and after equilibration of the soil at a potential of -60 cm of water

Whereas the direct-drilled soil gained water, except in the surface 5 cm, during equilibration, water was lost from soil which had been ploughed. It is evident therefore that, despite the generally lower water content (v/v) the water potential was higher in the ploughed soil at the time of collection. The higher potential could allow more water to be lost by evaporation from ploughed land, especially as the soil surface is rougher, and this may partly explain the lower water content of the surface soil after ploughing.

Preliminary measurements of the air capacity of soil at a potential of -60 cm H_2O (the volume of pores greater than 50 μm in diameter) showed a marked contrast between the direct-drilled and ploughed soil above about 25 cm, the air capacity of the latter being considerably greater (fig. 13). At a grassland reference area, it has been observed that air capacity was appreciably higher in the upper 5 cm, probably because of the greater content of organic matter and plant roots.

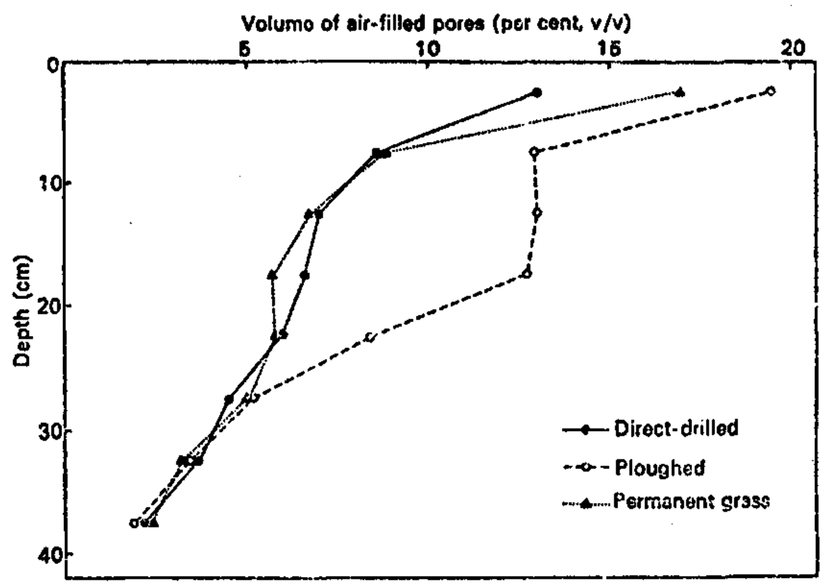

Fig. 13. Volume of air-filled pores (>50 μm in diameter) at different depths in direct-drilled, ploughed land and under permanent grass on a clay soil (Denchworth series)

GRASSLAND RESEARCH INSTITUTE
HURLEY, MAIDENHEAD, BERKSHIRE

1. THE GRASSLAND RESEARCH INSTITUTE is concerned with the growth and utilization of forage crops that make maximum use of the radiant energy of the sun and the nutrients available in the soil.

Investigations into irrigation and the efficiency of water use by grass and forage crops are in progress, giving particular attention to the rate of uptake of soil water by different crops and from different soils and the effects of differences in water uptake on crop growth rate. The relationship between the location of water in the soil profile and the availability of plant nutrients is considered (Agronomy department).

The Botany department undertakes measurement of radiation, temperature, relative humidity, wind speed and carbon dioxide content within and above the herbage crop, with direct measurements of carbon dioxide and water vapour exchange of the crop. Investigations are in progress to study the relationship between the aerial environment, leaf diffusion resistance and leaf water status of grasses and the relationship between crop transpiration, carbon dioxide exchange and crop growth. Another interest is the loss of water from cut forage crops during field drying.

2. INVESTIGATIONS IN PROGRESS

2.1. Systems analysis

An empirical model to calculate the uptake of nitrogen by the grass plant, effect of nitrogen on plant growth and changes in available nitrogen in the soil profile is being established. Since soil water content and soil temperature are very important for transformations of N in soil, detailed sub-models have been developed and tested against experimental data. The soil temperature sub-model calculates daily variation of temperature at regular intervals down the soil profile, using air temperature as a data input. The other submodel simulates daily variations in soil moisture content and water movement down the soil profile. The soil moisture extraction is evaluated with a simple balance equation, supposing the evaporative demand is satisfied by the water available in the profile, linearly decreasing from field capacity to the wilting point. The potential evapotranspiration is evaluated according to Penman's formula. Nitrogen uptake is proportional to the water uptake.

Results calculated show reasonable agreement with the available experimental data.

2.2. Botany department

Since a much larger part of British grassland is harvested by grazing than by cutting, this group is concentrating its attention on the growth of the grazed sward. The objective is to understand the principles which govern growth of the crop which is harvested by grazing animals and to discover how the sward responds to changes in grazing management. This study will provide a rational basis for the design of grazing strategies and for the improvement of utilization under grazing. A further objective is to compare different estimates of sward production: (a) through physiological measurements; (b) by short-term exclusion of animals from the sward with cages;and (c) from measurements of forage intake by animals.

Another factor which concerns the utilization of forage is the loss of water after cutting for hay or silage: rapid water loss after cutting is critical for succesfull hay making and for pre-wilted silage.

A comparison between cutting and grazing management is shown in fig. 14 for S23 perennial ryegrass sward.

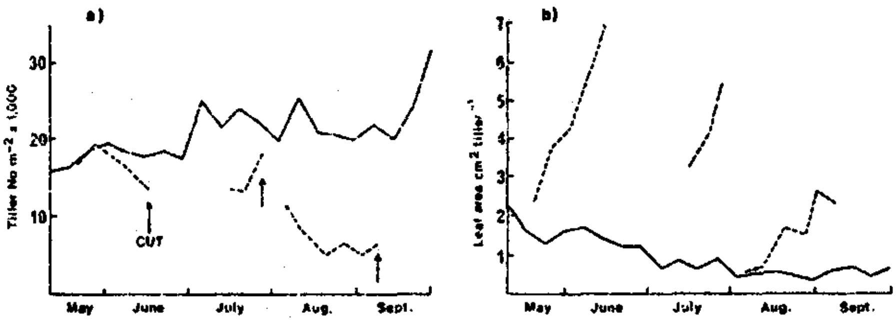

Fig. 14. Tillers numbers (a) and leaf area per tiller (b) in grazed or infrequently cut -----swards of S 23 perennial ryegrass, 1977. (Second growth period in the cut sward not measured)

Fig. 14a shows the number of tillers in grazed and cut swards throughout the growing season. Where grazing began in early May, tiller numbers in both sward were 16 - 17 000 m^{-2}. In the cut sward, tiller numbers first increased and then declined steadily during the first (flowering) growth period, so that by the time the sward was cut in mid June there were 13 000 tillers m^{-2}. In subsequent vegetative regrowths, tiller numbers exceeded the spring values and declined during July and August to around 6 000 tillers m^{-2}. In contrast, tiller numbers increased in the grazed sward, albeit irregularly, throughout the year, exceeding 20 000 m^{-2} throughout July and August and 30 000 in the autumn. Fig. 12b shows the consequences of these two patterns of tiller production on tiller size. Mean leaf area per tiller showed a characteristic increase during each successive growth period between cuts, using 7 cm^{-2} in the flowering sward and over 5 cm^{-2} in the vegetative regrowths. In marked contrast, mean leaf area per tiller in the grazed sward only exceeded 2 cm^{-2} at one assessment in the spring, and thereafter declined steadily through the season to values less than 0.5 cm^{-2} per tiller.

More attention will be paid in future to the physiology and growth of roots and effect of the physiological environment within the soil, since a mathematical simulation model set up to estimate the growth of the grass crop, predicted with considerable accuracy the above ground production, whereas the prediction of root growth was poor.

NATIONAL VEGETABLE RESEARCH STATION
WELLESBOURNE WARWICK

1. NATIONAL VEGETABLE RESEARCH STATION is mainly concerned with research into methods of improving the yield and quality of vegetables. Recent hydrologic work has been concerned with the water balance of cropped and uncropped soil, as it effects the movement and uptake by plants of nutrients and herbicides in the soil.

A means of forecasting the distribution of nitrogen in soil and its availability to plant roots from standard meteorological data and laboratory measurements on soil is being developed. It is being done by testing a model for upward and downward movement of ions, studying the effect of soil moisture and texture on the transport of nitrate through the soil roots and developing quantitative information about microbial activities. A computer model for the redistribution of water in fallow soil has been developed and is being tested by field and laboratory experiments. The model is being extended to account for the uptake of water by plants using standard meteorological data and laboratory measurement of soil properties. The work includes the construction of simple empirical models for the spatial development of root systems in the soil.

Quantitative relations about soil/plant processes are being combined into dynamic models for predicting the effects of various agronomic practices, and of soil and weather conditions on the responses of crops to fertilizers in field. The validity of the models are being tested in detailed experiments at Wellesbourne, at EHS stations and on growers' holdings.

2. INVESTIGATIONS IN PROGRESS

2.1. Soil Science Department

2.1.1. Soil physical conditions

A mathematical model has been developed to simulate the vertical distribution of water, including water extraction by plant roots.

For uncropped soils, the model calculates the flow of water, the water content and the matric potential for any depth, using meteorological data and soil hydraulic properties. The soil is assumed to consist of a stack of horizontal layers; from the known starting water contents of each layer and the known soil hydraulic properties, the instantaneous flow rates between the adjacent layers are calculated. The flows at the top and the bottom of stack are also calculated from the boundary conditions. These flows are used to calculate the new water content of each layer after a small time increment. The calculations are repeated for the next time increment and so on; the series of small time steps approximating the true continuous process.

The input data required and the variables that can be obtained in the output are listed in table 4.

List of model input and output data

Input data	Source
Rainfall	From meteorological records
Penman Eo	
Water Distribution at time = 0	Measured
Matric suction at 60 cm	
pF - water content relationship	
Hydraulic Conductivity - water content relationship	Measured
Diffusivity - Water content relationship	
Number and thickness of soil layers	As described in text
Length of time step	

Output data
Instantaneous or accumulated water fluxes at any depth or time
Water content or matric potential at any depth or time

A comparison between the simulated and measured pF values is shown in fig. 15.

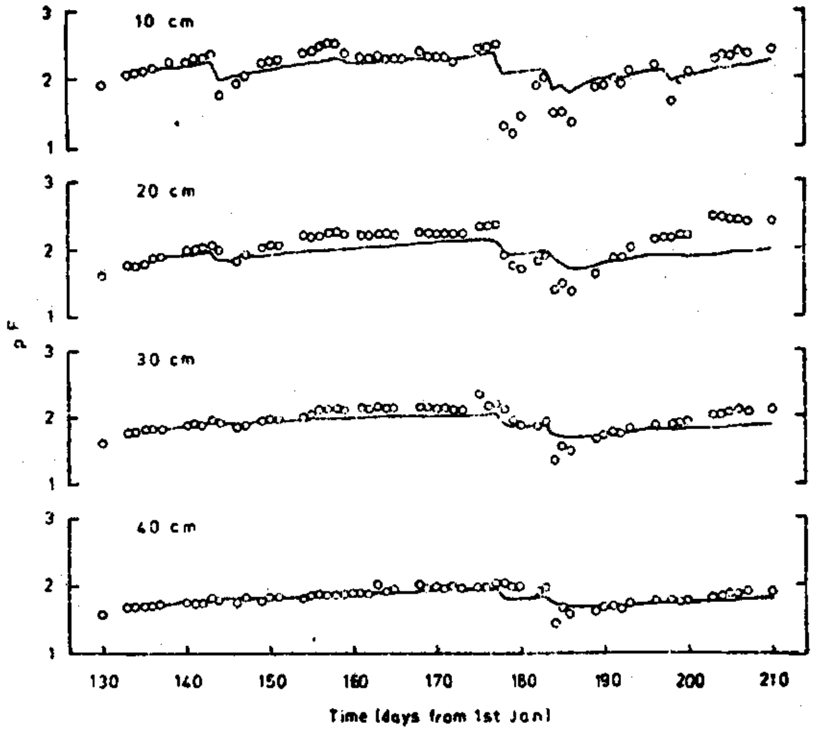

Fig. 15. Measured (points) and simulated (line) changes in pF at several depths in the field soil

Fig. 16 shows soil water distribution as measured with the neutron probe and those calculated by the model. Changes in water contents were generally less than .002 by volume while the variation between neutron probe tubes was large.

This model has been developed to include water extraction by plant roots. Results from the model agreed well with field measurements, the main differences being caused by horizontal variations in root density, hysteresis in the soil hydraulic properties and by apparently anomalous infiltration behaviour of the field soil.

The root water extraction term is calculated from

$$S = \Delta z\ L(h_s - h_p)/(R_s + R_p) \qquad (*)$$

where

Δz = thickness of the layer

L = root length per unit soil volume

h_s = bulk soil pressure head

h_p = plant water potential

R_s = soil resistance $\quad (R_s = \dfrac{\ln(r_s^2/r_r^2)}{4\pi\ \bar{k}})$

R_p = plant resistance

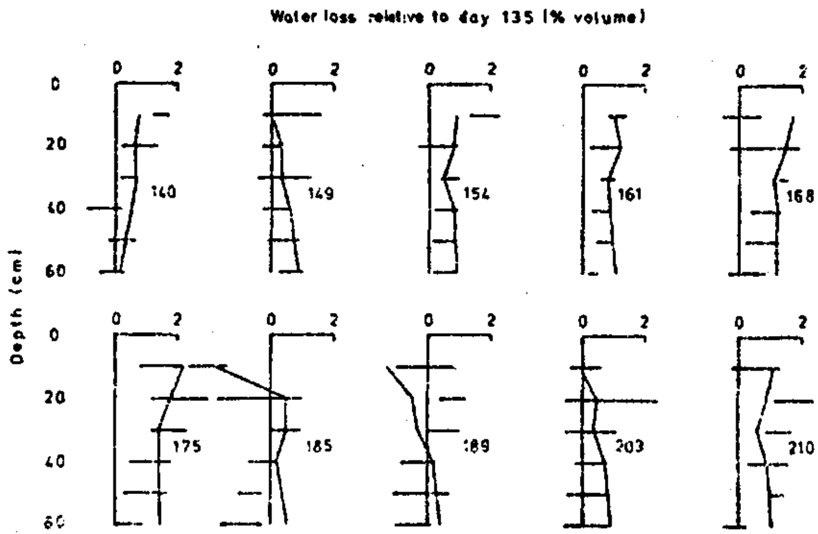

Fig. 16. Water loss relative to day 135. Measured points are shown as their mean $\pm$ SD, simulated data shown by the line

The Hansen and Hillel approximation (*) do not have to make the improbable assumption of a constant potential at the root surface, as

$$S = k(h_s - h_p)/b$$

but neither Hansen or Hillel have published any comparisons of their models with experiments.

Fig. 17 shows a comparison of the simulated pF's and those measured with a set of tensiometers for different depths.

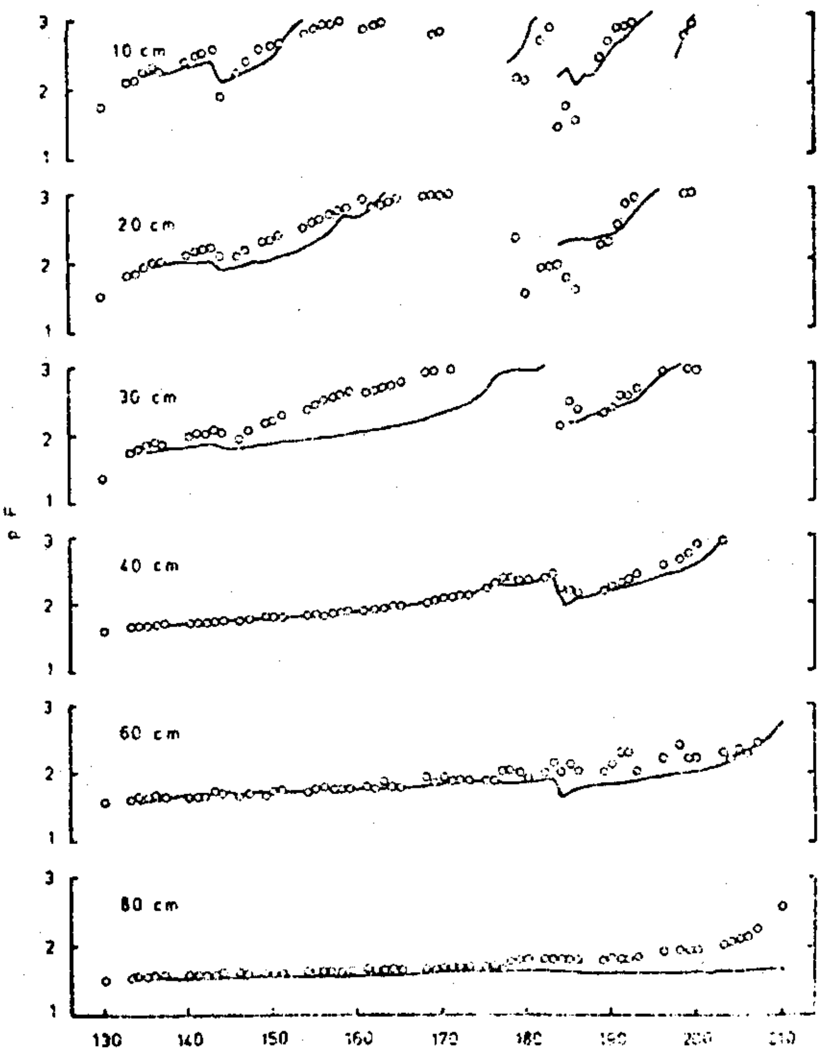

Fig. 17. Comparison of measured pF values (points) with those calculated by the model (line)

The neutron probe measurements and the simulated changes in percent volumetric water content for depths down to 80 cm are shown in fig. 18.

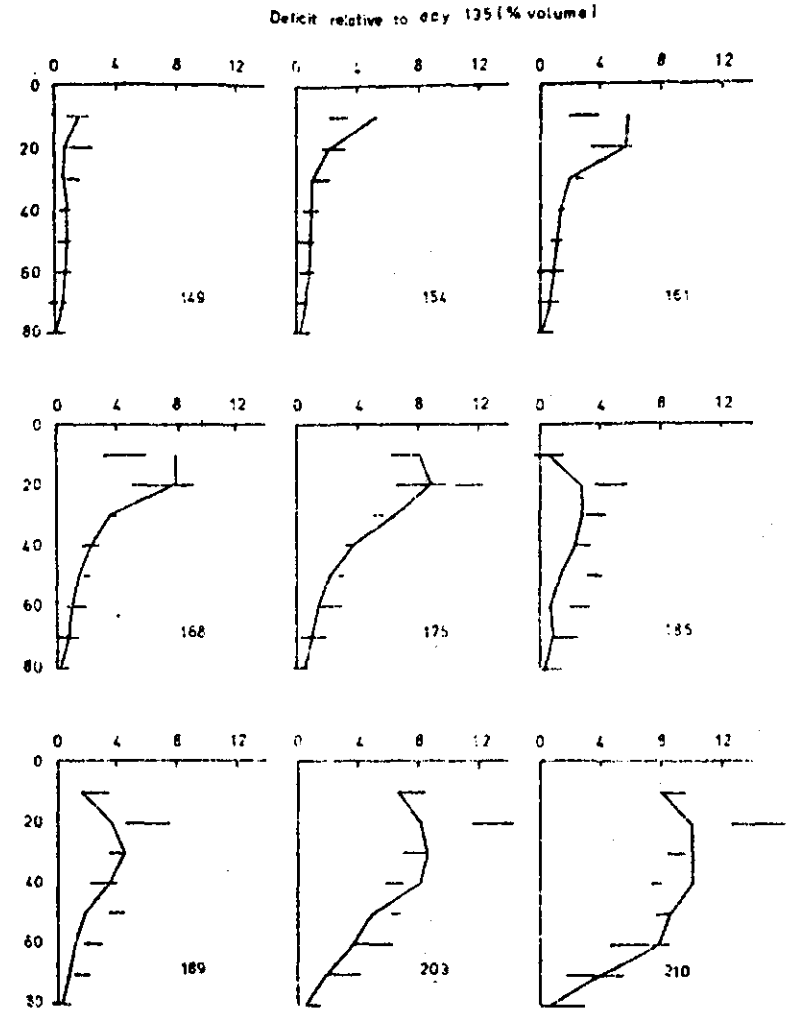

Fig. 18. Comparison of measured water extraction patterns (shown as mean ± SD) with those calculated by the model (line)

Root resistance. Early runs of the model with a variable root resistance show that the value of root resistance at a plant potential of -9 bars (the water potential at which the stomata are assumed to close) had the dominant effect on the calculated extraction patterns. This is because it affects the stage in the drying cycle when stomatal closure occurs, causing the transpiration to fall below the potential rate. A fixed root resistance of .22 10^5 day cm^{-1} estimated from Brouwer's data for a potential of -9 bars gave results almost identical to those calculated from a water potential-dependent resistance derived from the same data. A fixed resistance of $.22 \times 10^5$ day cm^{-1} was therefore used in the model. The highest root resistance reported by Brouwer was about 1.4×10^5 day cm^{-1}. Newman has measured a value of 9.25×10^5 day cm^{-1}, but this value, as he suggests, represents a maximum root resistance rather than a typical one.

Fig. 19 shows the simulated water distribution obtained by using these root resistances compared with the measured values for three occasions. The results obtained from Brouwer's maximum resistance (1.4×10^5 day cm^{-1}) are more ambiguous. The fit to the experimental data is only slightly worse than that of the basic model and may not be significantly worse if all the approximations and assumptions involved could be evaluated.

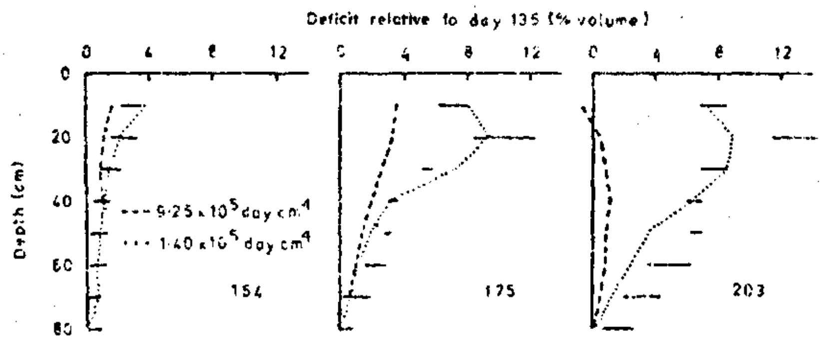

Fig. 19. Effect of various root resistances - (Rp) on calculated extraction patterns. Measured results shown as mean $\pm$ SD

The authors of the model indicated two important conclusions. Firstly it would appear that to calculate water extraction, the value of root resistance is not very critical. In their opinion, this could explain the good agreement between model and experiment that has been obtained by some workers even when unlikely assumptions are made about the mechanisms of flow through the roots. Secondly, the good fit obtained by ignoring some important factors (as an interface resistance between the soil and the root and an increasing resistance associated with non uniform root distributions) does not preclude their existance.

2.1.2. Stem thickness gauge

The conventional field method for measuring crop water stress with a pressure chamber is labour intensive, destructive of plant material and does not permit continuous measurements. In the soil science department, work has started on a technique which gives an indirect measurement of water stress by measuring changes in stem diameter with a linear variable differential transducer (LVDT). The output from this device can be recorded automatically with a very handy data logger, so that in principle it is possible to obtain a continuous estimate of water stress throughout the life of the crop for many plants at same time (fig. 20-21).

2.1.3. Leaching of nitrate and salts

Leaching of nitrate results primarily from the upward and downward flow of water in soil. All models for leaching start from the hypothesis that the rates of flow of water or the distribution of soil water down the profile are known at least approximately during the entire leaching period.

Several models have been developed at the National Vegetable Research Station to study the leaching problems.

a) Simulation model for the leaching of adsorbed and unadsorbed anions

The profile is divided into layers, each one characterized by a maximum and minimum water content (the field capacity and evaporation limit respectively). The model includes routines for estimating both the downward leaching of salts (after excess rainfall or irrigation) and the capillary movement of anions to the soil surface (after evaporation). Daily amounts of rainfall and evaporation are applied to the surface and the redistribution of water and salts is calculated (on a layer-to-layer basis) from the initial water and salt contents of each layer by adding or subtracting water to or from the moisture content until the stated maximum or minimum value

Fig. 20. Linear variable differential transformer (LVDT)

Fig. 21. A very handy data logger

is reached. Adsorption-desorption processes are defined by a generalized isotherm equation which can be adapted to either the linear or Langmuir form, or a combination of the two.

The model was tested using field data for soluble unadsorbed anions and published data for adsorbed ones.

b) Throughout the soil/plant system, electroneutrality is maintained and pH does not change within the plant. When roots take up more nutrient cations than anions, H^+ ions are released and conversely when they take up more anions than cations, OH^- ions are released from the root surfaces. It has been deduced that

$$\frac{dC}{dt} = \frac{dN}{dt} \frac{(f_1+f_2)}{1+k} + \frac{dA}{dt}$$

where dC is the increment in total cations, dN in organic -N, and dA in inorganic anions over a short time interval dt; f_1 and f_2 are respectively the reduction of NO_3-N and production of SO_4, expressed as fractions of the rate of production of N. This equation should apply to all crops, whether nutrient supplies are optimum or sub-optimum. The evidence suggests that when crops are grown with sufficient nutrients for maximum growth, then the coefficients, for a given crop on a given soil, are constant throughout the growth period. On the other hand, if there is any deficiency, one of the coefficients changes rapidly with time.

UNIVERSITY OF NOTTINGHAM
SCHOOL OF AGRICULTURE
SUTTON BONINGTON, LOUGHBOROUGH
Department of Physiology and Environmental Studies

1. LIBYAN PROJECT

The thermal maps of Wadi Al Shatti (Libya) showed a strange behaviour of temperature of sand dunes in comparison with the moisted areas (sebkhas). The daytime flight registered a lower temperature, in correspondence of the dunes than in the sebkhas. Furthermore, the night flight registered a higher temperature in correspondence of the dunes, than in the sebkhas. While discussing this problem with prof. Monteith, he suggested to take into account the surface roughness in order to justify that strange behaviour of the soil temperature. Other suggestions: to use the Penman-Monteith equation to evaluate surface resistances (cropped soils) or surface humidity (bare soil), using an independent estimation of the actual evaporation or transpiration rates (as Bowen ratio). The surface resistance and humidity can be used as boundary condition for a flow simulation model, and to introduce the stability correction in the estimation of actual evaporation by Bowen ratio method.

Following these suggestions, some attempts have been made to evaluate the role of surface roughness in the variability of temperature: first results confirm this hypothesis, but the calculated differences of temperatures of these two zones are lower than the actual ones.

2. EVAPORATION FROM A CATCHMENT

Estimates of evaporation from a catchment (Kingston Brook) were compared with rainfall and runoff measured by the Trent River Authority. The use of water by different types of vegetation was explored and the depth of water extraction by roots related to plant and soil characteristics. Soil water content was measured with a neutron probe and a method was developed to estimate drainage and evaporation rates separately. A linear relationship between annual rainfall and annual runoff for 1969/76 was interpreted in terms of a fixed catchment storage (125 mm), a small and nearly constant winter evaporation (ca 49 mm), and a summer evaporation from storage plus a constant fraction of contemporary rainfall.

During the winter, monthly evaporation estimates were consistently less than the corresponding differences between rainfall and runoff mainly because of a gradual increase in catchment storage due to gradual swelling of the clay soils. During the spring, storage in the catchment declined in response to both increasing evaporation losses and the continued high drainage rates from the soil.

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