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THE INFLUENCE OF DIFFERENT WATER AND NITROGEN LEVELS ON CROP GROWTH, WATER USE AND YIELD, AND THE VALIDATION OF CROP MODELS

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by

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EXECUTIVE SUMMARY

THE INFLUENCE OF DIFFERENT WATER AND NITROGEN LEVELS ON CROP GROWTH, WATER USE AND YIELD, AND THE VALIDATION OF CROP MODELS

Water is in high demand in South Africa, so it is imperative that the use of irrigation water be optimized. This multi-disciplinary project arose out of a need to gain a better understanding of crop growth and water use. With the improvement of crop simulation models in mind, field experiments were designed to answer specific questions where information was lacking. The aims of the study centred around characterizing the interactive effects of water and nitrogen on the growth, water use and yield of irrigated spring wheat. A comprehensive series of field measurements was made over four seasons, and the information was then used to validate various crop models.

The detailed objectives for this project had three main focus areas:

(i) To characterize the development of the crop canopy and the resistances to water flow in the soil-plant-atmosphere continuum under different water-nitrogen regimes (in a field experiment).

(ii) To validate, under South African conditions, selected crop models used in irrigation planning and management, and to make recommendations for improvements.

(iii) To test the reliability of the BEWAB irrigation scheduling program under the different water-nitrogen regimes, particularly in connection with the water use, water use efficiency and yield predictions.

The characterization of crop canopy development was undertaken in great detail in all four wheat seasons by means of growth (e.g. leaf area and biomass) and physiological (e.g. photosynthesis) measurements. A detailed study of the often neglected crop root system was also made, with the help of a minirhizotron video camera system. Plant water relations were monitored by means of leaf water potential measurements, and the rate of sap flow through a single stem was successfully measured after adapting and calibrating the heat pulse method.

The CERES, PUTU and SHOOTGRO wheat crop growth models, selected as typical of those in current use, were calibrated and validated under South African conditions using the comprehensive dataset generated in the field experiments. The ability of the models to accurately simulate various aspects of wheat production was tested under different levels of applied water and nitrogen. Certain inadequacies were highlighted which could enable model developers to make the necessary refinements.

The BEWAB irrigation program was used to schedule the irrigation throughout the four-year project, and although it was developed in a cooler region it proved to be quite reliable in a warm irrigation area such as Roodeplaat, when tested against measured yield and water use data. However, certain modifications could now be made by the developers of BEWAB, based on the information gained in this project, which would broaden its application base.

One of the major achievements in this project was that several specialized scientific techniques were adapted and brought to an operational level for wheat crop measurements:

Firstly, the heat pulse system, which had previously been used only on plants with robust stems such as soybeans, was adapted for use with thin-stemmed wheat tillers. The technique was then calibrated and used to make continuous measurements of single stem transpiration under field conditions. The success of this development will allow the heat pulse system to be used to study the transpiration of a wide range of plants, including grasses.

Secondly, a video camera was used to non-destructively monitor root growth and development by means of minirhizotron tubes installed in the soil under the wheat crop. This technique is new in South Africa and was evaluated in comparison with the destructive coring method. It allows a much more detailed study to be made of the root system than was previously possible, and is particularly suited to monitoring root turnover over long periods.

Thirdly, a detailed field evaluation was undertaken of a system for measuring single leaf photosynthesis. Guidelines were developed for the precautions necessary when using a leaf chamber in order to obtain accurate measurements on a routine basis. The technique was then used to establish the relationship between photosynthesis, leaf age and leaf nitrogen content for wheat leaves throughout the growing season.

Another valuable contribution arising from this study was the guidelines developed for farmers regarding the amount of irrigation water to apply and the optimal nitrogen application recommended for a specific target wheat yield in the warm irrigation region. For example, for spring wheat cultivars grown in a deep soil with a high clay content, in order to obtain a grain yield of 6-7 t ha^{-1} then a nitrogen fertilizer application rate of 135 kg N ha^{-1} is recommended. The Roodeplaat study indicated that a seasonal water use of approximately 550 mm would be required for this target yield if irrigation was applied weekly, but only 440 mm if it was applied once every two weeks. The efficiency of irrigation water could thus be improved if these guidelines are followed, and a higher yield produced per unit of irrigation water applied.

The main legacy of the project will be the large and comprehensive dataset that was generated, which characterizes the effects of different water and nitrogen application levels on the growth, water use and yield of a spring wheat crop. This information will be of great value both from a scientific standpoint, in that the processes involved are now better understood, and in the calibration, validation and refinement of crop growth models. The dataset is now available to any scientist who is able to make further use of it. In this way it is felt that the study has contributed to the furtherance of agricultural science in South Africa at the present time, and that the effect of the scientific progress will be realised in the years to come.

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The Steering Committee responsible for this project comprised the following persons:

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The Influence of Different Water and Nitrogen Levels on Crop Growth, Water Use and Yield, and the Validation of Crop Models

Chapter 1

INTRODUCTION

The demand on the water resources of South Africa is increasing rapidly due to urbanization and industrial development. This increases the competition for agricultural water from the mining and industrial sectors and from urban areas. It is therefore of prime importance that agricultural water use should be optimized. It is predicted that irrigation farmers will have to pay a higher price for their water in the future and there will thus be a need to optimize the economics of irrigation (Backeberg, 1989). In 1987, two of the priorities that were classified as essential (KKBN, 1987) included the development of an irrigation scheduling strategy to minimise the negative effects of plant water stress during water deficit, and the development of crop growth simulation models for South African conditions with the emphasis on water-yield relationships.

Progress has been made towards these ends by various groups in South Africa, including the University of Orange Free State and the Institute for Soil, Climate and Water (ISCW), and further research that would complement the existing projects was proposed. As the expertise at ISCW includes agrometeorologists, soil scientists and plant scientists, it was the ideal place for a multi-disciplinary project. The existing state of the science of crop water use was assessed and gaps in knowledge were identified. This project was built around the crop simulation models, and field experiments were designed to answer specific questions where information was lacking.

Crop simulation models form a basis for this project, but they can only be improved if the mechanisms involved in the soil-plant-atmosphere water continuum are understood. To best be able to predict the effect of water shortage on crop growth, development and production, a mechanistic model is needed. Various models were investigated during this project, which included field experiments to calibrate and validate them for the prevailing conditions at Roodeplaat. This would enable one to make recommendations for improvements and adaptations to the models.

During the project, four wheat and three soybean experiments were conducted at Roodeplaat. Plant growth and development were investigated under optimal and limiting conditions of both water and nitrogen applications. Soil water content was regularly monitored, and as the climate plays an important role in the water stress conditions of a crop, weather measurements were made continuously during the trials. The growth and development of both the crop canopy and root system were monitored. Often in a project of this type a study of the below-ground biomass is neglected due to practical difficulties, but an attempt to overcome these was made by the use of a minirhizotron video camera system. This was one of several specialized techniques that were used during the experiments. Plant production was monitored in detail by measuring the leaf photosynthesis with respect to leaf age. As plant growth is dependent on the transport of water from the roots to the leaves, it was also important to investigate transpiration. The various components of the system were studied with the use of an adapted heat pulse method for measuring water flow through a single stem.

All this science must be related back to the farmers, and so technology transfer is of vital importance. Although the detailed scientific investigations cannot be explained to the farmers, the increased knowledge obtained can be used to improve the models. Adaptations and improvements to each model are best undertaken by the original developer, so the datasets produced by this project will be made available to other scientists working with crop simulation and irrigation scheduling models.

Chapter 2

OBJECTIVES

The objectives for this project had three main focus areas:

(i) To characterize the development of the crop canopy and the resistances to water flow in the soil-plant-atmosphere continuum under different water-nitrogen regimes (in a field experiment).

(ii) To validate, under South African conditions, selected crop models used in irrigation planning and management, and to make recommendations for improvements.

(iii) To test the reliability of the BEWAB irrigation scheduling program under the different water-nitrogen regimes, particularly in connection with the water use, water use efficiency and yield predictions.

Chapter 3

GENERAL MATERIALS AND METHODS

The main field study in this project comprised the four wheat (*Triticum aestivum* L.) experiments carried out during the winters of 1990, 1991, 1992 and 1993. Three soybean (*Glycine max* L.) experiments were also performed, in the summers of 1990-91, 1991-92 and 1992-93. The virtual absence of rainfall during the winter allowed irrigation levels to be closely controlled, and therefore a range of water treatments from dryland to well-watered was possible in the wheat experiments. However, such control was impossible during the rainy summer months, except in the small area available under the two rain shelters. An attempt was made to maintain several water treatments in the soybean experiments, but unpredictable rainfall levels made it very difficult to make meaningful comparisons between them, and especially between years. It is for this reason that this report will concentrate on results from the wheat study.

3.1 Roodeplaat Soils

3.1.1 WHEAT

The four wheat experiments were carried out alternately on two sites in successive years at the ISCW Roodeplaat Experimental Station (see plan in Appendix 1).

During the 1991 and 1993 seasons the experiments were located in the area closest to the buildings and weather station. The soil here had been cultivated by the research team for several years and therefore information on profile depth, drainage and clay content, and other physical and chemical data, was already available. Based on this information the most suitable position was selected to plant the wheat crop. A few routine analyses were carried out in both years to check the soil fertility and pH.

During the 1990 and 1992 seasons the experiments were located in an area to the west of the above site, on the other side of the road. Initially this was a relatively "virgin" soil, having been cultivated only once before, in the summer of 1989-90. Since there was no soil physical or chemical information available, it was considered necessary to undertake a detailed analysis prior to the 1990 experiment. A database was thus created, which would be of use if, for example, problems with crop growth were detected. Soil samples were taken from different depths on a grid basis covering the whole experimental area, and a range of physical and chemical tests were performed. A few routine analyses were subsequently repeated in 1992.

The soil type on the two experimental sites was a Hutton of the Ventersdorp family, with a profile depth of 1.9-2.1 m and an average bulk density of 1.5 g cm^{-3}. Tables 3.1 and 3.2 give chemical and physical data respectively for the 1990/1992 site. Table 3.3 gives chemical data for the 1991/1993 site.

Table 3.1 Soil chemical data for the wheat 1990/1992 site.

Soil depth (cm)	Element (mg kg^{-1})					
	P	K	Ca	Mg	pH(H_2O)	pH(KCl)
0-15	10.4	135.6	798	348	7.02	5.83
15-30	8.4	129.6	796	350	6.93	5.81
30-60	4.2	68.7	988	423	7.26	5.98
60-90	2.5	55.0	1038	433	7.60	6.36
90-120	1.8	42.7	942	405	7.63	6.49
120-150	1.5	38.2	910	385	7.50	6.27
150-180	1.2	38.8	865	368	7.46	6.16
180-210	1.0	39.3	920	366	7.48	6.19

Table 3.2 Soil physical data for the wheat 1990/1992 site.

Soil depth (cm)	Fractional distribution (%)						
	Coarse sand	Medium sand	Fine sand	Very fine sand	Coarse silt	Fine silt	Clay
0-15	4.49	20.14	22.45	7.92	9.06	10.70	23.48
15-30	4.52	20.04	22.12	7.86	9.16	10.80	24.04
30-60	3.69	17.06	18.01	6.30	7.73	10.67	35.14
60-90	4.04	17.08	17.53	6.00	6.81	9.05	38.04
90-120	3.75	17.55	19.52	6.63	7.10	9.13	34.56
120-150	3.65	17.39	20.03	7.02	7.58	9.58	33.34
150-180	3.69	17.45	20.20	7.07	7.70	10.16	32.17
180-210	3.64	17.99	21.22	7.19	7.30	10.13	30.95

Table 3.3 Soil chemical data for the wheat 1991/1993 site.

Soil depth (cm)	Element (mg kg^{-1})					
	P	K	Ca	Mg	Zn	pH(H_2O)
0-30	30.6	157.6	790	253	2.1	6.30
30-60	19.4	111.0	862	288	0.7	6.35

3.1.2 SOYBEAN

The three soybean experiments of 1990-91, 1991-92 and 1992-93 were all carried out in the area closest to the buildings, where the rain shelters are located (see plan in Appendix 1). Soil properties were therefore similar to those given for the 1991/1993 wheat experimental site.

3.2 Roodeplaat Weather

A range of weather variables were measured continuously throughout the four years of this project, at an automatic weather station located on the northern edge of the 1991/1993 wheat experimental site.

Air temperature was measured hourly in a standard Stevenson screen, and mean, maximum and minimum values determined. Rainfall, solar radiation (via a solarimeter) and wind run (via an anemometer) were also measured hourly, and daily totals calculated. The evaporation from a US class A pan was recorded daily. These parameters were logged by a datalogger and the data dumped via tape into a computer each week.

Where the above records are incomplete due to periodic equipment failure, data (including humidity) have been obtained from the ISCW AgroMet databank for the main Roodeplaat weather station, located approximately 1 km S.E. of our station. (See Appendix 2 for long-term data for Roodeplaat.)

3.3 Soil Preparation and Crop Production

3.3.1 WHEAT

The soil was prepared in as similar a manner as possible prior to each of the wheat experiments in order to minimize effects on the crop. Firstly, the land was kept as free of weeds as was practically possible during the period when not in use for experiments. However, in order to optimize the effect of nitrogen application rates, a summer crop was planted to extract as much nitrogen as possible from the soil. Grass was grown prior to the 1990 experiment (with sorghum following it), while a maize crop preceded (and followed) the 1991, 1992 and 1993 experiments. In the winter months the weeds on the unused site were slashed and the soil lay fallow. As a result of the four experiments being carried out on alternate sites, the rotation prior to the 1992 and 1993 experiments comprised a summer crop, a fallow winter, another summer crop, then the experiment.

The crop cultivation methods used were generally the same as those employed by a modern wheat farmer. Firstly the soil was ploughed, and approximately 48 kg ha^{-1} P (in the form of superphosphate 10.5) applied. The soil was then rotovated to prepare a fine seedbed. The wheat was planted with a precision planter at a density of 60 seeds m^{-1} row. Row spacing was 25 cm. The planting date in the four wheat experiments was 25 May in 1990, 1992 and 1993, and 27 May in 1991. After planting, the land was lightly irrigated to ensure germination. Three weeks after planting the nitrogen treatments were applied. Ammonium sulphate nitrate was dissolved in water and applied to each plot by means of a system of microjets. More water was then applied to "wash" the nitrogen into the soil. About one month after planting the crop was sprayed with Buctril to control the weeds. After anthesis the plots were covered with nets to prevent bird damage. These nets were specially manufactured to give a shading effect of less than 7 %.

3.3.2 SOYBEAN

The 1991-92 soybean experiment directly followed the 1991 wheat crop on the same site, whilst the 1990-91 and 1992-93 experiments were both preceded by a maize crop. In all cases the soil was ploughed and then rotovated to prepare the seedbed. The soybean seeds were inoculated then planted with a precision planter at a density of 16 seeds m^{-1} row. Row spacing was 50 cm. The planting dates in the three experiments were 14 November 1990, 19 November 1991 and 10 December 1992. After planting, the land was lightly irrigated to ensure germination. During the season weeds were removed by hand.

3.4 Design and Layout of Experiments

3.4.1 WHEAT

The effect of different irrigation and nitrogen treatments on the growth and water use of spring wheat was studied using the cultivar SST86. The main trial in each experiment was irrigated by means of a linesource sprinkler system. This applies water in such a way that the greatest amount falls close to the line, with the volume decreasing linearly with distance away from it. This made it possible to apply five irrigation levels, and these five water treatments were labelled W1 (no water) through to W5 (well-watered). The amount of water to be applied at each irrigation was determined by predictions made using the BEWAB program (see Chapters 8 and 9). Rain gauges were positioned on either side of the linesource to record the actual amount of water applied. The W2, W3, W4 and W5 treatments received seasonal totals of approximately 250, 370, 500 and 650 mm of water respectively. During the 1990 and 1991 seasons, two linesource systems were operated simultaneously to provide two irrigation frequencies: once a week and once every two weeks. In 1992 and 1993 only the weekly frequency was used.

The layout of each linesource experiment was in the form of a factorial "pseudo split plot" design. There were four replicate blocks, two on either side of the linesource (except in 1990 when there were only three). Each block comprised 25 plots (each measuring 6 x 3 m) to give 25 water/nitrogen treatment combinations. Within each of the five water treatments there were five levels of nitrogen application, labelled N0 (zero) through to N4. In 1990 the rates used were those given in the original project proposal, namely 0, 50, 100, 150 and 200 kg N ha^{-1}, regardless of water treatment. However, in 1991, 1992 and 1993 the rates were changed so that less nitrogen was applied on the dry treatments and more on the wetter ones (Table 3.4). Diagrams of the linesource experimental layout for the four wheat seasons are given in Appendix 1.

Table 3.4 Nitrogen levels (kg N ha^{-1}) applied to wheat in 1991-1993.

Water treatment	Nitrogen treatment				
	N0	N1	N2	N3	N4
W5	0	75	150	225	300
W4	0	60	120	180	240
W3	0	45	90	135	180
W2	0	30	60	90	120
W1	0	25	50	75	100

In 1991, 1992 and 1993, selected water/nitrogen treatments were replicated a further three times in larger (10 x 5 m) "physiology" plots, for the purposes of carrying out a series of detailed crop physiological measurements. The treatments were chosen to cover the range of the main experiment and comprised two nitrogen application rates (N0 and N3) and three irrigation levels (W1, W3 and W5). These plots were irrigated individually using one of two smaller moveable linear irrigation systems. The layout of the physiology plots for each season is shown in Appendix 1. In 1992 and 1993 two additional W5N3 plots were included (labelled W5AN3) to measure the lower limit of soil water required by the crop, which received no water after anthesis (i.e. W5 until 94 days after planting (DAP) in 1992 and 100 DAP in 1993, then W1). In 1993 two further plots were added specifically to study the effect on root growth of renewing the water supply at anthesis. The first, labelled W1AN3, began the experiment as a W1 treatment then reverted to W5 from 107 DAP. The second, W3AN3, began as a W3 treatment, became W1 at 79 DAP, then W5 from 107 DAP.

In 1990 and 1991 defoliation experiments were carried out, irrigated using the linesource system (see Chapter 7, section 7.3).

In 1992 a trial was planted with two additional wheat cultivars, SST44 and SST66, for the purposes of the crop model study (see Chapter 10). The planting date was the same as for the main wheat experiment. The linesource system was used to provide three levels of irrigation (W1, W3 and W5), and there were two nitrogen application rates (N0 and N3). Plot size was 3 x 5 m.

3.4.2 SOYBEAN

The effect of different irrigation frequency treatments on the growth and water use of soybean was studied using the cultivars Forest, Hutton, Ibis and Impala in 1990-91, cv. Hutton and Impala in 1991-92 and cv. Hutton and Prima in 1992-93. There were four treatments in 1990-91: irrigation was carried out every 3, 7, 14 and 21 days, until the soil profile was full (approximately 420 mm). In subsequent experiments the 7 d treatment was omitted. There were three replicate 10 x 5 m plots for each treatment, in a completely randomized design. They were irrigated individually using one of two moveable linear irrigation systems. Additional 14 and 21 d plots under the two manually-operated rain shelters were irrigated using a fixed system of microjet sprayers. The layouts for the three experiments are shown in Appendix 1.

3.5 Data Collection

The measurements made in each experiment are summarized in Table 3.5, and details concerning the archiving of the data are given in Appendix 5. The specialized techniques that were used during this project are described in Chapter 4. The GENSTAT program was used for statistical analysis of the data.

3.5.1 WHEAT

Soil water content and final yield were measured in every plot, but after 1990 most other data was obtained from the physiology plots only.

Crop canopy development and growth were monitored throughout each season, across the range of W/N treatments, by means of weekly leaf area and above ground plant biomass measurements. In 1990 and 1992 daily leaf length measurements were also made. In 1991 and 1993 the percentage ground cover was monitored as the crop developed using a linear photosynthetically active radiation meter positioned diagonally between the rows. Root length and mass were estimated by extracting soil cores several times during each season, whilst in 1992 and 1993 a minirhizotron video camera system was also used for a more detailed study of root development.

In the centre of each plot a neutron moisture meter access tube was installed to a depth of 1.8 m following crop emergence. Soil water content was measured weekly, prior to irrigation. Tensiometers were also installed in 1993 (two replicates at depths of 30, 60 and 90 cm in one of the W5N3 and W1N3 physiology plots). Crop water status was monitored via measurements of leaf water potential (twice-weekly at midday and weekly pre-dawn) using a PMS pressure chamber. In 1990, 1991 and 1992 stomatal diffusive resistance was also measured (using a LICOR porometer), and in 1990, leaf osmotic potential. In 1991, 1992 and 1993 single leaf photosynthesis measurements were made, and the same leaves analyzed for their nitrogen content. In 1992 and 1993 the heat pulse method was used to measure transpiration rate per tiller.

3.5.2 SOYBEAN

In all three soybean experiments routine measurements were made of soil water content and plant biomass, leaf area, final yield and midday leaf water potential. In 1991-92 and 1992-93 root growth was monitored using both the minirhizotron and core methods, transpiration was measured using the heat pulse technique, and single leaf photosynthesis measurements were made. In 1992-93 only, two replicate tensiometers were installed at depths of 30, 60 and 90 cm in the cv. Hutton 21 d plot under the rain shelter and the adjacent 3 d plot. Stomatal resistance and pre-dawn leaf water potential measurements were also made in 1992-93.

Table 3.5 Summary of soil and crop measurements made during the wheat and soybean experiments.

MEASUREMENT	WHEAT				SOYBEAN		
	90	91	92	93	90-91	91-92	92-93
SOIL							
Water content	x	x	x	x	x	x	x
Water potential				x			x
N content		x	x	x			
pH	x		x				
Chemistry	x	x					
Physics	x						
CROP							
Yield	x	x	x	x	x	x	x
Biomass	x	x	x	x	x	x	x
Leaf area	x	x	x	x	x	x	x
Leaf length	x		x				
% ground cover		x		x			
Water potential	x	x	x	x	x	x	x
Osmotic potential	x						
Stomatal resistance	x	x	x				x
Transpiration			x	x		x	x
Photosynthesis		x	x	x		x	x
N content		x	x	x			
Root length	x	x	x	x		x	x

Chapter 4

SPECIALIZED TECHNIQUES

4.1 Single Leaf Photosynthesis Measurements

Of fundamental importance in crop productivity studies is the accurate and precise measurement of photosynthesis (P_N). In this project a portable system was used to measure the photosynthetic activity of single wheat leaves. However, such measurements are heavily influenced by the environmental conditions under which they are made, as well as by inconsistancies in technique. This can lead to unreliable and inaccurate results. A study was therefore conducted to investigate the effect on P_N of variations in the procedures and techniques followed during field use of the single leaf photosynthesis system (in collaboration with Dr. D.M. Oosterhuis of the University of Arkansas, USA, during his visit in 1991). The system was then used to compare P_N rates in wheat grown under different water and nitrogen treatments (see Chapter 5).

4.1.1 MATERIALS & METHODS

During the 1991 wheat experiment a series of tests was performed to evaluate the effect of variations in both measurement procedure and leaf environment on the rate of P_N recorded by a LICOR LI6200 portable photosynthesis system. For each measurement, between six and ten similarly exposed leaves in a single physiology plot were used to calculate a mean value.

4.1.2 RESULTS & DISCUSSION

4.1.2.1 Diurnal P_N

A comparison of diurnal P_N measurements made at two-hourly intervals throughout the daylight hours on well-watered and dryland treatments is shown in Fig. 4.1. Respiration (R_P) rates are also given (measured by covering the sample chamber with a black cloth and aluminium foil after the leaf was sealed inside). The diurnal trend of P_N rate exhibited a rapid increase soon after sunrise until a midday plateau between 11:00 and 14:00, after which it began to decline sharply. The effect of water stress could easily be detected. There was little change in R_P rate during the daylight hours.

4.1.2.2 Leaf Damage

Care must be exercised not to bend or break the midrib during the measurement procedure. Damage to the leaf blade during measurement was found to result in abnormally low P_N readings (Fig. 4.2(a)). After the leaf is sealed in the chamber it must be held as close as possible to its natural orientation to the sun in order to obtain a meaningful and representative measurement.

4.1.2.3 Breath

As the LICOR system calculates P_N from the decline in CO_2 concentration in the leaf chamber, sudden changes in CO_2 must be avoided. Even one breath on or near the leaf tip protruding from the closed chamber was disruptive to the measurement and caused erroneous results (Fig. 4.2(b)).

4.1.2.4 Shadows

Solar radiative flux density is the driving force for P_N, so any change in the incident radiation due to clouds or shadows will drastically influence the P_N measurement. The effect of lowering the irradiance by shading the leaf after it was sealed into the sample chamber is shown in Fig. 4.3. The P_N rate began to decline about 3 s after shading and was close to zero after about 10 s. When the shadow was removed after only 20-30 s then the P_N rate returned to normal after another 10-15 s had elapsed.

4.1.2.5 Position on the Leaf

Measurements were usually made on the middle section of the leaf blade. When compared with both the tip and base sections (Fig. 4.4(a)), P_N rates measured in the middle or near the tip of the leaf blade were found to be similar, but both were higher than that recorded near the base of the leaf and significantly greater than on the leaf sheath.

4.1.2.6 Position in the Canopy

The different leaves on the stem have different P_N rates according to their age. The lower two leaves have a P_N rate of between a half and a third of that of the upper leaves (Fig. 4.4(b)). When these measurements were made the flag leaf was not yet fully expanded and so it had a slightly lower P_N rate than leaf 8.

4.1.3 CONCLUSION

Precise and reliable measurements of wheat leaf P_N can be routinely made in the field provided adequate attention is given to the measurement procedure. Necessary precautions include measuring at the same time each day and on leaves at similar insertion levels in the crop canopy. Abnormal shadows and breathing on the leaf must be avoided, and the correct exposure and orientation of the leaf during the measurement period must be maintained.

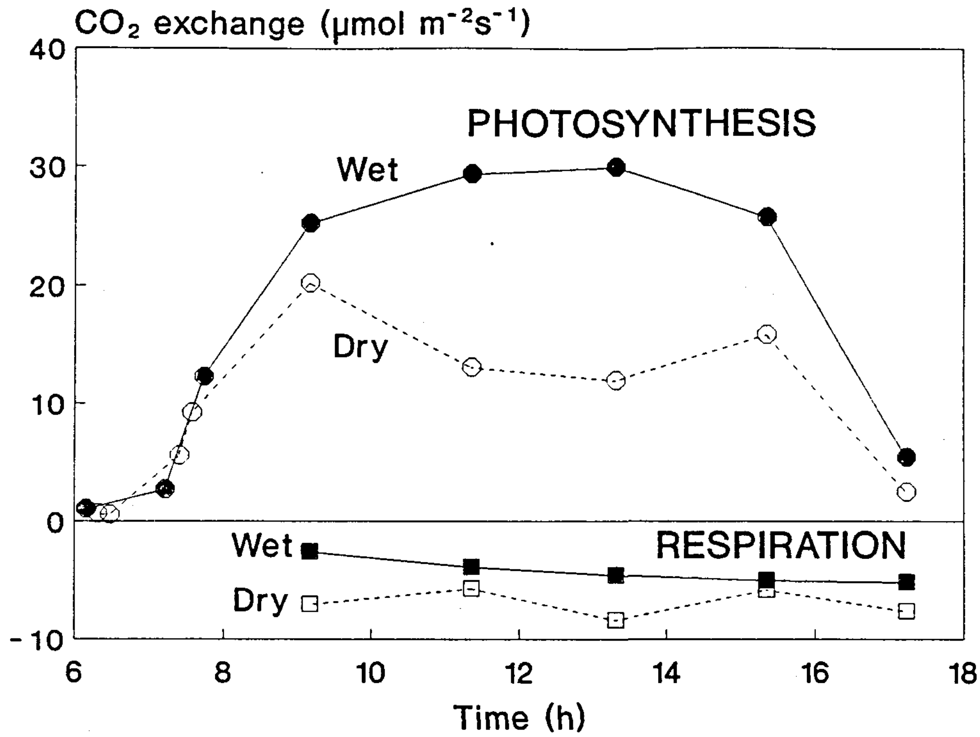


Fig. 4.1 Diurnal changes in P_N and R_P of leaf 8 recorded 72 DAP in the 1991 wheat experiment.

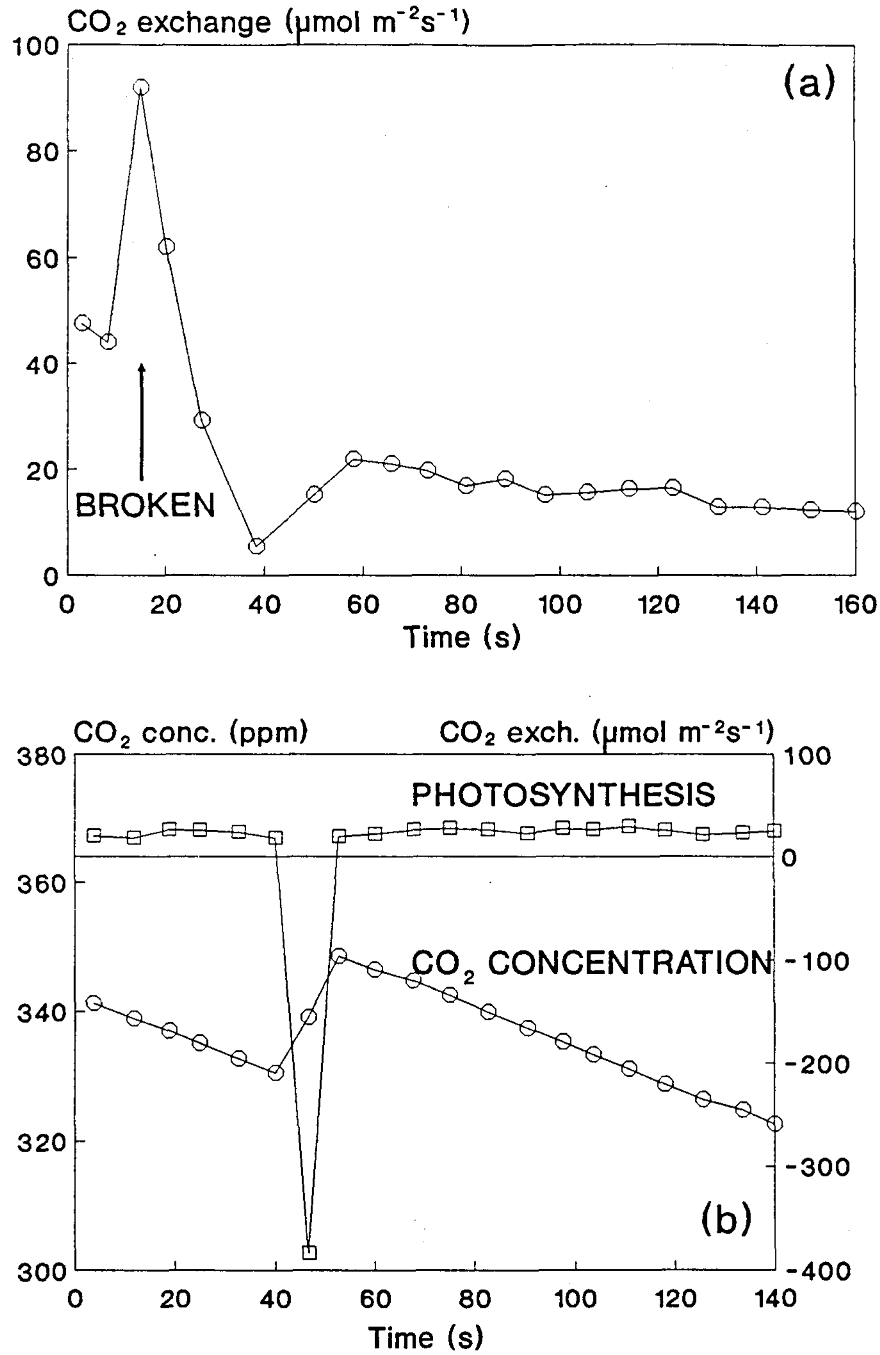


Fig. 4.2 The effect on P_N measurement of (a) a crack in the leaf, and (b) a single breath on the exposed part of the leaf.

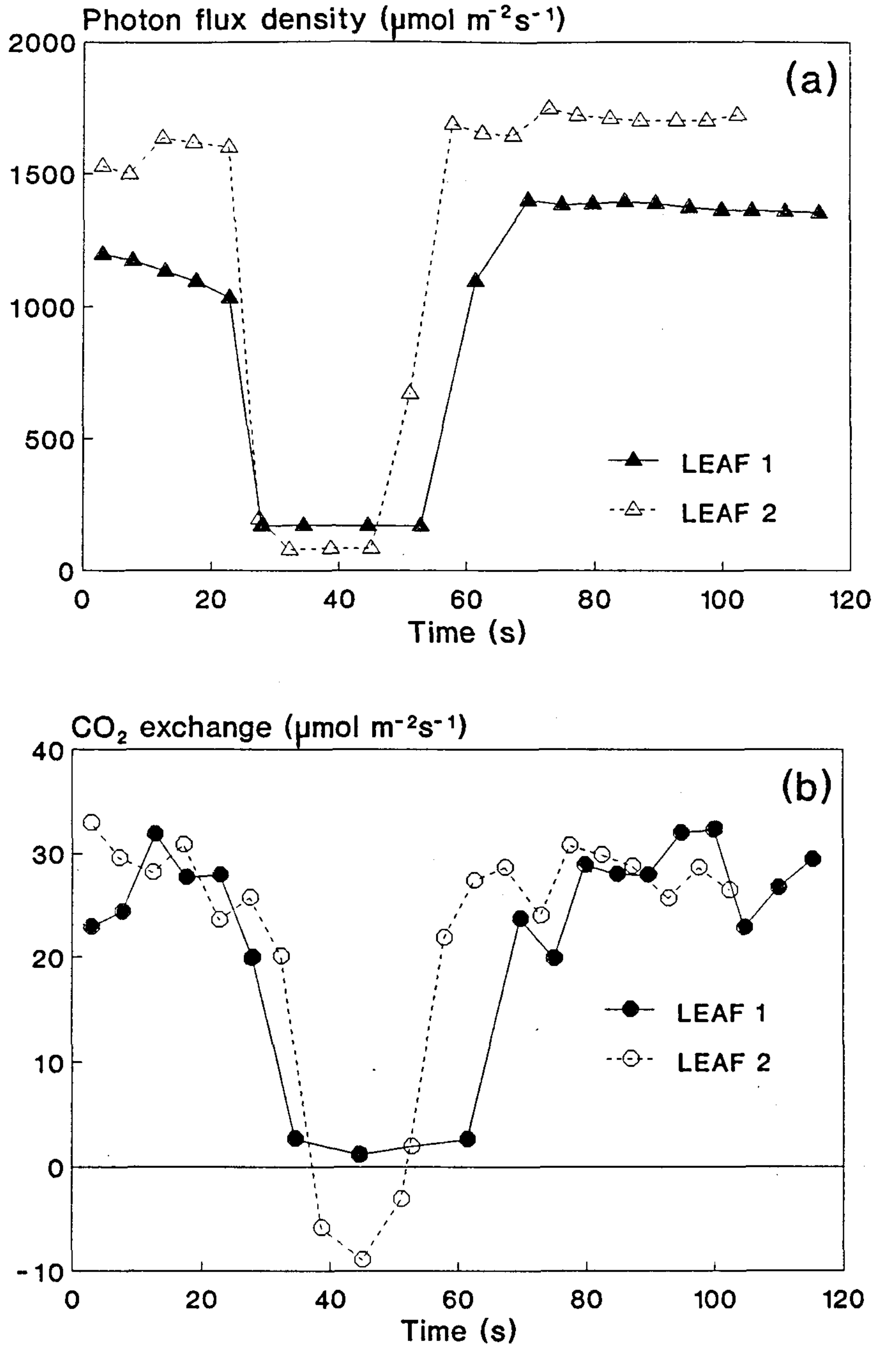


Fig. 4.3 The change in (a) radiation and (b) P_N measured when a leaf was suddenly shaded and then re-exposed to full sunlight.

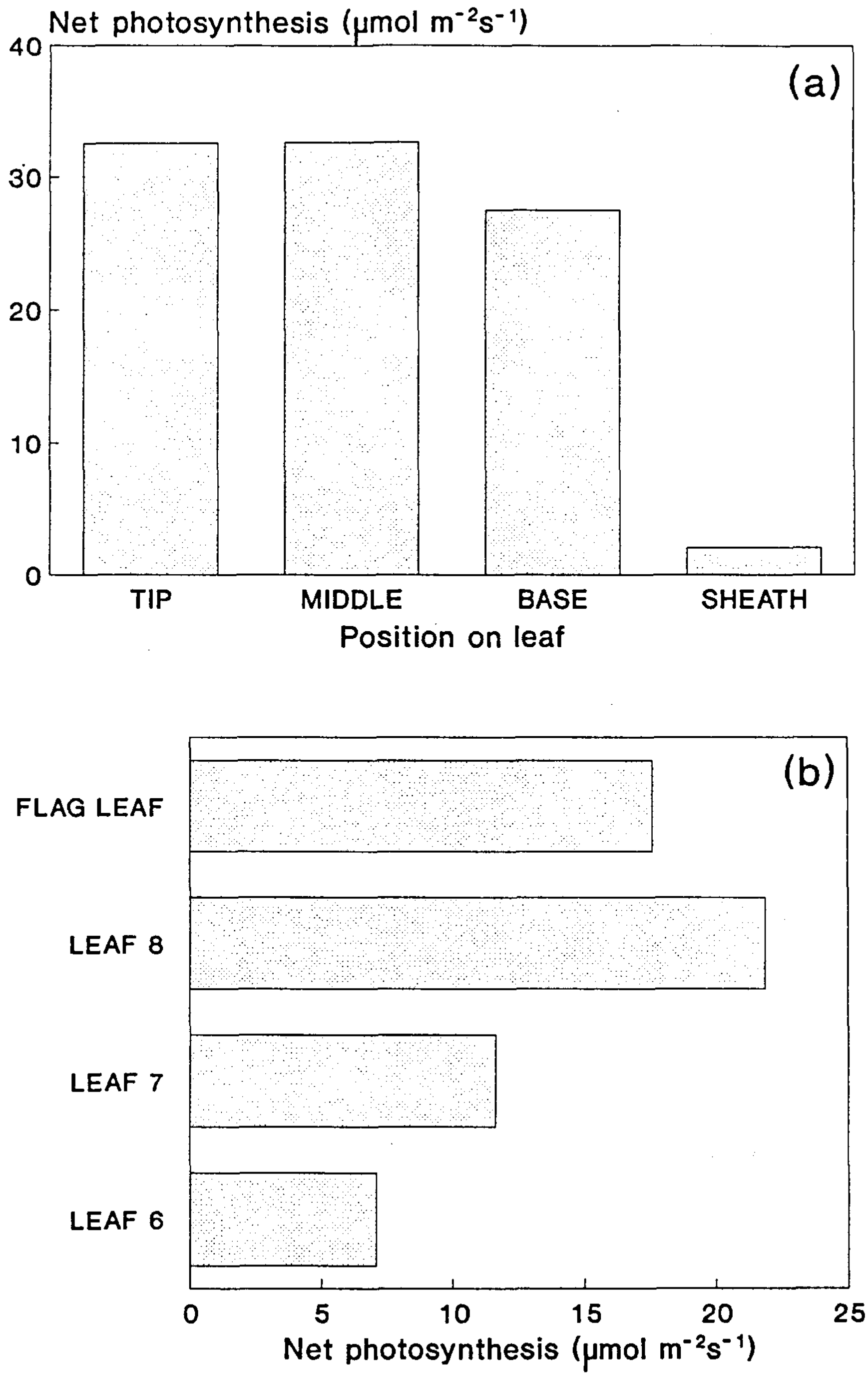


Fig. 4.4 The effect on P_N of measuring at (a) different positions on a single leaf blade, and (b) different positions on the plant.

4.2 Heat Pulse Technique for Measuring Transpiration

The heat pulse system is used to monitor the transpiration of a single plant by measuring the rate of sap flow in its stem. The technique was developed for trees (Cohen, Fuchs & Green, 1981; Cohen, Kelliher & Black, 1985) and the system was subsequently miniaturized and used on agronomic crops such as cotton and maize (Cohen, Fuchs, Falkenflug & Moreshet, 1988; Cohen, Huck, Hesketh & Frederick, 1990). In this project the heat pulse system was used with soybeans, then further adapted for the delicate nature of a single wheat tiller (in collaboration with Dr. Y. Cohen of the Institute of Soils and Water, Volcani Center, Israel, during his visit in 1990). The method was first calibrated by measuring the water loss from plants growing in a weighing lysimeter, then used to compare the transpiration of plants grown under contrasting water and nitrogen treatments (see Chapter 6).

4.2.1 DESCRIPTION OF TECHNIQUE AND ADAPTATION FOR WHEAT

The heat pulse method uses the principle that a heat pulse applied to the stem will travel with the sap. The theory and instrumentation are described in detail by Cohen *et al.* (1988). The miniaturized probe block comprises a heater needle piercing the stem and two radially inserted thermocouple needles, one 9 mm above the heater (downstream) and the other 4 mm below, mounted on a 33 x 20 x 8 mm phenolic fibre plate. The heater needle (a modified stainless steel hypodermic needle, 33 mm long and 0.5 mm in diameter) is connected by electric cable to a heat pulse transmitter (Ariel HPT 5/10), powered by a 12 V battery. The thermocouple needles (each 7.5 mm long) are connected to a battery-powered Campbell Scientific CR7 datalogger. This is programmed to trigger the emission of a heat pulse every 30 min, and to monitor the difference in temperature (dT) between the two thermocouples every 0.7 s. Two time values are stored (see Fig. 4.5). One, t_0, is the time taken for dT to return to its initial value (a baseline measured during the minute immediately before the pulse is sent). The other, t_m, is the time taken for dT to reach its maximum. One of these values is then used to calculate heat velocity in the stem, dependent on whether the rate of sap flow is high or low. If it is low ($t_0 > 15$ s), heat velocity (v, mm s^{-1}) is estimated using the equation:

$$v = (x_1 - x_2)/2t_0 \qquad [4.1]$$

where x_1 and x_2 are the distances (mm) from the heater to the thermocouple needles above and below the heater respectively. The maximum t_0 value stored by the data logger is set at 250 s, and thus the default zero v is 0.01 mm s^{-1}. At lower heat velocities the errors in detecting t_0 become too great. At high sap flow rates t_0 is also difficult to detect because it is very short. In such instances, v can be estimated more accurately using t_m in the equation:

$$v = [(x_1^2 - 4kt_m)^{0.5}]/t_m \qquad [4.2]$$

where k (mm^2 s^{-1}) is the thermal diffusivity of the stem, determined by combining equations 4.1 and 4.2 when t_0 is between 12 and 15 s.

Stem sap flow rate measurements were limited to a maximum of ten plants at any one time by the capacity of the heat pulse transmitter. With a thick stem plant like soybean a hole needed to be drilled (using a guide) for the heater needle. It was then necessary to insulate the thermocouples from direct sunlight by positioning a piece of aluminium foil around the stem above the probe. Compared to single stem plants like soybean, each individual tiller of a wheat plant has a much lower sap flow rate due to its low leaf area. The monitoring of heat velocity is therefore subject to greater error, particularly due to the effects of direct sunlight and wind on the thermocouples in a more open canopy. This problem was overcome by positioning a piece of PVC pipe (80 mm long and 110 mm diameter) on the soil surface around the plant, filled with small polystyrene chips and covered with masking tape, to insulate the probe block. As the wheat stem is so small and delicate it was necessary to fit a piece of flexible plastic tubing (4 mm inside and 10 mm outside diameters and 40 mm long) around the stem to give it some strength and support. A hole in the tubing prevented heat dissipation from the heater needle to the plastic instead of the plant stem. Since the stem is hollow the heater needle was fitted through a node.

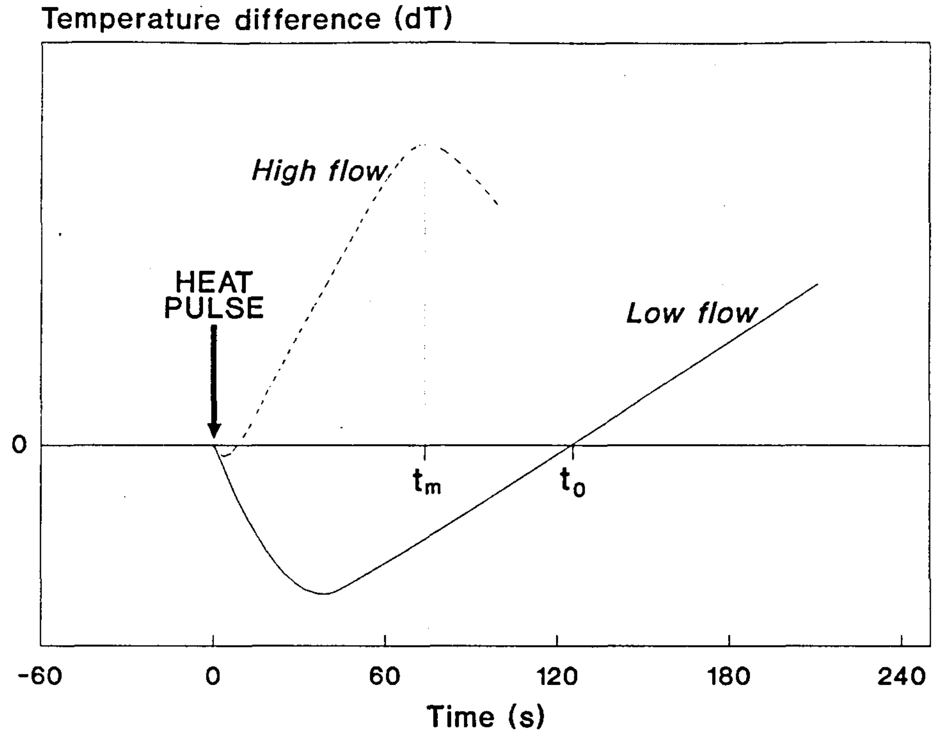


Fig. 4.5 Diagram showing the effect of sap flow rate on the temperature difference between the two thermocouples on the heat pulse probe, and the t_0 and t_m time values stored by the datalogger.

4.2.2 CALIBRATION

4.2.2.1 Wheat

Wheat was grown in a 2 x 2 x 1 m deep weighing lysimeter during the winter of 1992. This was not part of the main experiment, but a separate area planted 6 days earlier on 19 May. When stem elongation had ceased and the tillers were thick enough to support the probes, at 93 DAP ten representative main tillers were selected from an estimated total number of 1600 tillers in the lysimeter. The probes were then installed as described above, with the heater needle fitted through the second node up from the base of the stem. The diameter of this node was measured. Straw was placed on the lysimeter soil surface to inhibit evaporation, and the datalogger was programmed to record lysimeter mass every 30 min at the same time as t_0 (it is unnecessary to record t_m when heat velocity is consistently low as it is with wheat). Data were recorded continuously between 93 and 107 DAP, during which time the plants were irrigated twice. The correlation between T ($mm^3\ s^{-1}$), calculated from the rate of lysimeter weight loss every 30 min, and mean vA ($mm^3\ s^{-1}$), the product of heat velocity ($mm\ s^{-1}$) and the cross-sectional area of the stem node (mm^2), is shown in Fig. 4.6(a). After correcting the default zero vA to 0, the linear regression line (forced intercept) has the equation:

$$T = 1.047 * vA \qquad [4.3]$$

with $r^2 = 0.71$.

4.2.2.2 Soybean

Soybeans were grown in a weighing lysimeter as part of the 1991-92 experiment. When stem elongation had ceased, at 80 DAP ten representative plants were selected from the total of 86. A heat pulse probe block was fitted on the stem of each plant between the unifoliate and cotyledon nodes, as described above, and stem diameter at this point was measured. Straw was placed on the lysimeter soil surface to inhibit evaporation, and the datalogger was programmed to record lysimeter mass every 30 min at the same time as t_0 and t_m. The lysimeter was situated under a rainfall shelter, and the plants were subjected to a series of drying cycles between each irrigation. Data were recorded continuously from 84 DAP until the plants senesced at 133 DAP. The relationship between T, calculated from the rate of lysimeter weight loss every 30 min, and mean vA, the product of heat velocity and stem cross-sectional area, is shown in Fig. 4.6(b). After correcting the default zero vA to 0, the linear regression line (forced intercept) has the equation:

$$T = 1.175*vA \qquad [4.4]$$

with $r^2 = 0.81$.

The calibration coefficients for both wheat and soybean are close to 1, the figure given for soybean by Cohen, Takeuchi, Nozaka & Yano (1993). The reason for including stem cross-sectional area, A, in the heat velocity measurements is that the proportionality factor between T and v increases with A, which can be regarded as the effective sap conducting area (Cohen *et al.*, 1988). This was confirmed during a glasshouse pot calibration carried out with individual soybean plants. The results from this, and an unsuccessful attempt to carry out a similar controlled environment pot calibration with wheat, are not reported here. Since the wheat and soybean heat pulse calibration coefficients were required to interpret measurements of heat velocity made in the field, it was considered that use of the field lysimeter calibration results would be the most appropriate.

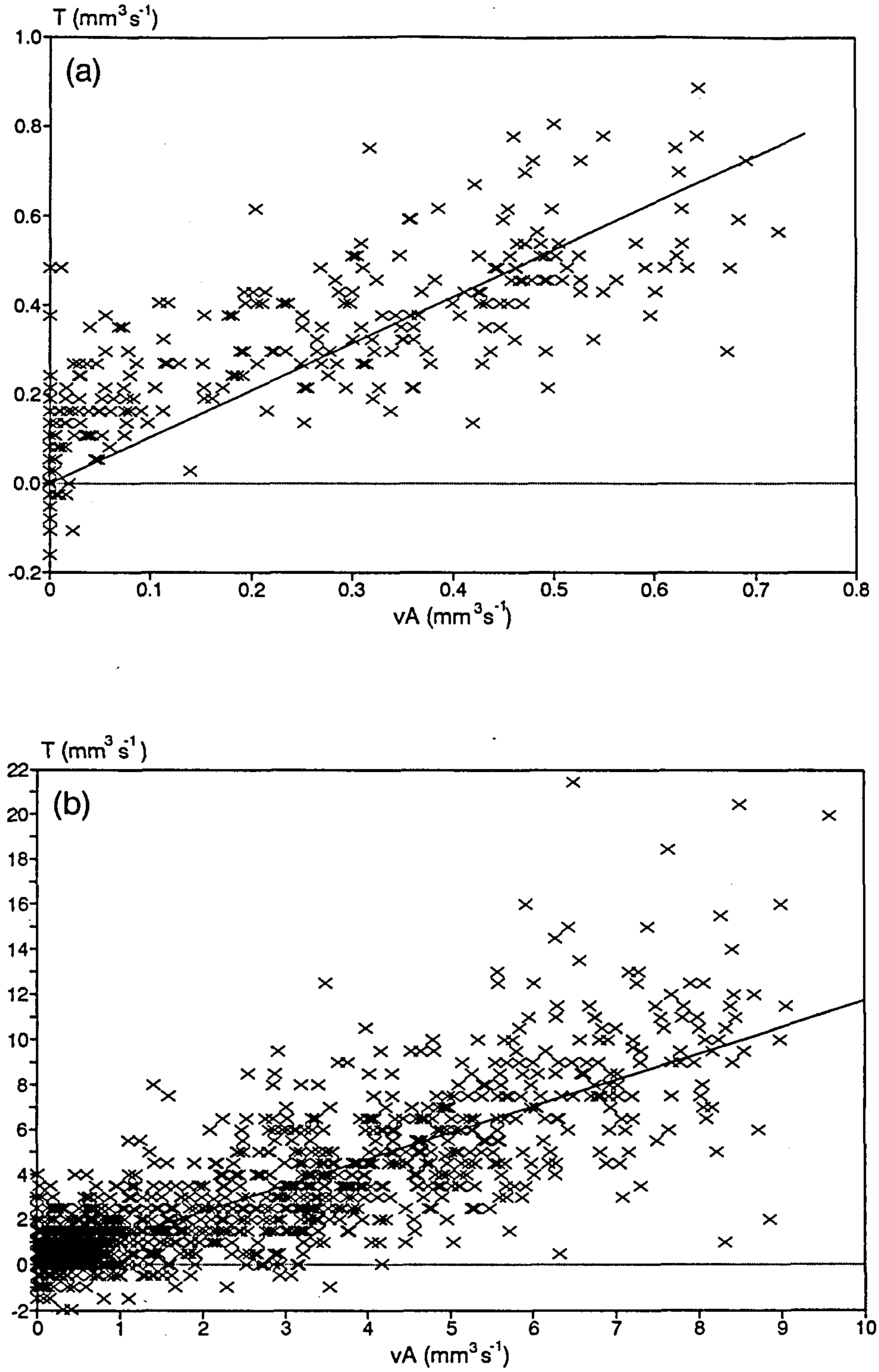


Fig. 4.6 The correlations for (a) wheat and (b) soybean between transpiration, T, calculated from the rate of lysimeter weight loss every 30 min, and mean vA, the product of heat velocity and stem (or node) cross-sectional area, (after correcting the default zero vA to 0). The data points are means from 10 plants and the equations of the linear regression lines (forced zero) are: (a) y = 1.047x (r^2 = 0.71) and (b) y = 1.175x (r^2 = 0.81).

4.3 Minirhizotron System for Monitoring Root Growth

Root growth is a very important component of crop production as it is the root system of a plant that gives it access to the water and nutrients in the soil which are vital for shoot growth. However, studies of the growth and development of roots are hampered by their inaccessability. The capacity for monitoring the root growth of a crop can be significantly increased by the use of a minirhizotron camera system. A minirhizotron is a transparent tube in the soil, into which a modified video camera is inserted. Roots that come into contact with the tube are observed on a small colour monitor. A video recorder is used to tape the images, allowing detailed root measurements to be made at a later stage in the laboratory. The minirhizotron system allows root growth and development to be studied in much greater detail than is possible with the labour-intensive and time-consuming soil core extraction method, and non-destructive root growth measurements may be made as frequently as those of the shoot.

Whilst the use of minirhizotron systems to study root growth has been well documented (see Taylor, 1987), few detailed comparisons have been made between field data obtained using this method and that from destructive methods. One of the aims of this study was to monitor the root growth of a crop using both the non-destructive minirhizotron and the destructive soil core methods. Root length data obtained from the cores was compared with that from the video images, and the relative strengths and weaknesses of the two methods were assessed.

4.3.1 MATERIALS & METHODS

A colour minirhizotron video camera was purchased from Bartz Technology Co., California, USA, in 1991. It has white and UV light sources at the lens (UV helps to distinguish live roots), and is connected via a flexible cable to a mains-powered control unit where light and focus can be adjusted. This unit is connected in turn to a compact, lightweight, combined LCD colour monitor and VHS video recorder (Philips Moving Video). A trolley, designed to fit between the crop rows, was constructed to transport this equipment in the field.

The minirhizotrons are 2 m long clear perspex tubes (54 mm inside and 60 mm outside diameter), sealed at the bottom end. They are inserted in the soil at an angle of 35° to the vertical by removing soil cores after crop emergence. To exclude light, the section of tube remaining above the soil surface is covered with black tape, and capped when not in use. A 2.1 m long, two segment indexing handle system allows the camera to be returned to exact locations in all tubes. An index hole drilled in the tube wall ensures that the camera will always descend the same viewing line along the upper surface of the tube. Numbered index holes in the handle allow the camera to be lowered at 13.5 mm intervals (frame height), with the operator recording the depth location on the tape with a microphone.

The minirhizotron video camera system was used to monitor root growth during the wheat experiments of 1992 and 1993 and the soybean experiments of 1991-92 and 1992-93.

4.3.1.1 Wheat

In 1992, a total of 24 tubes were installed at 30 days after planting (DAP), three in each of the three replicate W5N3 and W1N3 physiology plots, and one in each of three replicate W5N0 and W1N0 plots. In the plots with three tubes they were positioned (1) in a row and parallel to it, (2) between two rows and parallel to them, and (3) between two rows and perpendicular to them. In the plots with one tube it was placed in position 2. The angle of tube installation meant that the maximum depth at which roots could be observed was 1.35 m. Recordings were made nine times during the season, initially at weekly intervals (starting at 36 DAP) and later at 2-3 week intervals (ending at 150 DAP). On five of the recording dates (approximately 50, 75, 100, 125 and 150 DAP) soil core samples were taken for a destructive root length density determination. Three vertical cores (50 mm diameter) were removed from each of the three replicate plots of each treatment, one in a row and two adjacent to it. Sampling depth increased with time from an initial 1.05 m to 1.95 m at the fourth sampling. Each core was cut into 0-15, 15-45, 45-75, and subsequent 30 cm long sections. Each section was first broken in half in order to count the number of roots at the exposed surface (the core break technique; see section 4.4). Core sections from corresponding depths were then bulked for each plot, and the roots washed out of the soil, dried, and measured using a root length meter. The length of roots was expressed as cm cm^{-3}

of core volume (root length density, RLD) at each depth interval. (Root mass was also determined and expressed as mg cm^{-3}).

Core RLD data from the 50 DAP sampling were compared with that from the root video images, which were interpreted using four different techniques:

(i) Measuring the length of the roots in each image with a ruler from the monitor screen and converting into actual length to allow for the approximate four times magnification of the camera.

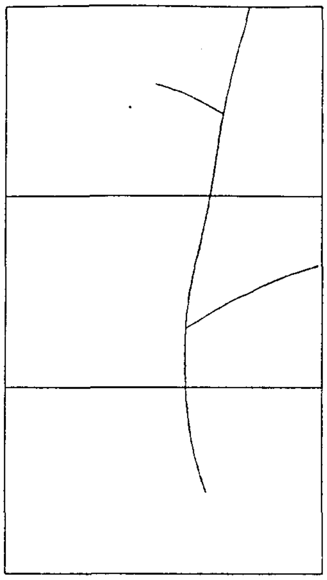
(ii) Counting the number of roots present in each image.

(iii) Counting the number of roots intersecting the border of each image (Buckland, Campbell, Mackie-Dawson, Horgan & Duff, 1993).

(iv) Counting the number of first and last points of contact between roots and tube in each image (Buckland *et al.*, 1993).

Fig. 4.7 illustrates the three counting techniques. In each case totals were calculated for the depth intervals 0-15, 15-45, 45-75, 75-105 and 105-135 cm, and expressed per cm depth. On the basis that the number of points of contact gave the best correlation with core RLD at 50 DAP (see section 4.3.2.1), and that this technique was a quick and easy one, it only was used to interpret the video images throughout the remainder of the season.

An image analysis system (J-L Automation IV120 with JLGENIAS 3.1 software) was used to capture selected root images from all 9 video recordings for the 3 tubes in the first replicate W5N3 and W1N3 plots. The same roots were thus compared over time, allowing any changes in diameter to be monitored.



No. of roots	No. of root intersections	No. of points of contact
2	1	1
2	2	0
1	1	1

Fig. 4.7 Diagram illustrating the three counting techniques used to interpret root video images from the 50 DAP sampling of the 1992 wheat experiment. Three consecutive images are shown. Due to the orientation of the camera the roots appear to grow upwards. The main root initially emerges from the soil and comes into contact with the tube in the first (bottom) image; it then intersects the upper border. The addition of a branch in the second image gives two more intersections but no points of contact since both roots grow on out of the image. However, the tip of the branch in the third (top) image is counted as a last point of contact.

In 1993 a similar procedure to the above was followed, except:
(i) At 36 DAP a total of 30 tubes were installed. The additional 6 tubes were installed in two extra plots (three in each, positioned as described above). These were labelled W1AN3 (W1 initially, then W5 from 107 DAP) and W3AN3 (W3 until 79 DAP, then W1, then W5 from 107 DAP) and their purpose was to study the effect on root growth of renewing the water supply at anthesis. Root images were also captured from video recordings made for these additional tubes in order to measure changes in diameter.
(ii) Recordings were made six times during the season (starting at 44 and ending at 126 DAP), and soil core samples were taken on four of these occasions (approx. 50, 75, 100 and 125 DAP).
(iii) Each core was cut into 0-15, 15-30, 30-45, 45-75, and subsequent 30 cm long sections.
(iv) Only the points of contact technique was used to interpret the video images.

4.3.1.2 Soybean

In 1991-92, 21 tubes were installed between 17 and 23 DAP, three in each of three replicate 3 d and 21 d irrigated plots outside the rainfall shelter, and three in the 21 d treatment under the shelter (all cv. Hutton). The three tubes in each plot were positioned as previously described for wheat. Recordings were made eight times during the season, initially at weekly intervals (starting at 23 DAP) and later at 2-3 week intervals (ending at 125 DAP). On six of the recording dates (34, 50, 62, 75, 100 and 125 DAP) 35.5 mm diameter core samples were extracted in the manner described above. Sampling depth increased with time from an initial 0.9 m to 1.5 m at the third sampling. Each core was cut into 0-15, 15-30, 30-60, 60-90 and subsequent 30 cm long sections, and then treated as described for wheat. The video recordings were replayed in the laboratory and interpreted using the points of contact method, with totals calculated for the depth intervals 0-15, 15-30, 30-60, 60-90 and 90-120 cm, and expressed per cm depth. A comparison with the length method of interpretation was made at 50 DAP.

In 1992-93, a total of 24 tubes were installed between 25 and 28 DAP, but this time all in position 2 (between two rows and parallel to them). Six tubes were located in the 21 d irrigated plot under the rainfall shelter and six in the adjacent 3 d treatment outside the shelter, for both cv. Hutton and Prima. Recordings were made five times during the season (starting at 32 and ending at 100 DAP), and interpreted using the points of contact technique, with totals calculated for the revised depth intervals of 0-15, 15-45, 45-75, 75-105 and 105-135 cm. On three of the recording dates (50, 61 and 75 DAP) three 50 mm diameter core samples were extracted from each plot, to a depth of 1.35 m. Each core was cut into 0-15, 15-45, 45-75, and subsequent 30 cm long sections. However, this time these cores were not bulked but treated as replicates.

4.3.2 RESULTS & DISCUSSION

4.3.2.1 Wheat

Initially it was thought that measuring the length of the roots in each video image would be the most accurate method of obtaining root growth data from the minirhizotron recordings. However, as root growth of the 1992 crop became more prolific after 66 DAP, distinguishing and measuring the roots on the screen became an increasingly difficult and lengthy process, and an alternative method was sought. During a visit by Dr. Fyfield to the University of Aberdeen, Scotland, to explore the possibilities of image analysis systems, discussions were also held with minirhizotron experts at the Macauley Land Use Research Institute. They suggested using the (then unpublished) points of contact technique. The correlations between core RLD and both minirhizotron root length and number of points of contact (PC) at the 50 DAP sampling are shown in Fig. 4.8. The data points are derived from all depth intervals below 15 cm, and are means from three replicate plots and tubes (i.e. 9 tubes, where available). When treated separately, tube position in the crop appeared to have no effect on the correlation (data not shown), and thus the three tubes in each plot were treated as replicates. The other two interpretation techniques, counting the number of roots or root intersections, gave very similar correlations to the root length method. One reason why counting points of contact gives the best correlation is that it largely eliminates the effects of tracking, i.e. roots which, despite the tube being installed on an angle, persist in following it for an unnaturally long distance. As illustrated in Fig. 4.7, such roots are ignored after their initial contact with the tube. Buckland *et al.* (1993) proposed a theoretical transformation for converting points of contact to root length density, but with wheat root data at 50 DAP their formula gave results an order of magnitude higher than values obtained from the cores, and was thus not used.

The reason why the data points in Fig. 4.8 were derived from depth intervals below 15 cm only is clear from Fig. 4.9, in which data from Fig. 4.8(b) is repeated to show the different depths, but now also includes values from the 0-15 cm layer. Regardless of which technique was used to interpret the root video images, the minirhizotron system greatly underestimated root length in this surface layer, where the highest core RLD was consistently found. Such a result for measurements at depths of 0-30 cm is common amongst users of minirhizotrons and has been well documented (see Taylor, 1987). (The reason is not known, but one suggestion is that heat conducted down the top section of the tube disrupts normal root growth in the adjacent soil. Better insulation of the exposed portion of the tube may therefore be required.) Fig. 4.10(a) shows the correlation between core RLD and the number of minirhizotron points of contact for all five sampling dates on which the two methods were used. Data points from the 0-15 cm layer have again been omitted, but there are still two obvious outliers deriving from the 15-45 cm layer. If these are ignored then a correlation coefficient of 0.33 is obtained. Whilst this is not as good as at 50 DAP only, it compares favourably with the value of $r = 0.28$ ($r^2 < 0.1$) obtained by Majdi, Smucker & Persson (1992) when comparing the two methods of root measurement in a maize crop. Irrigation or nitrogen treatment had no effect on the correlation.

Since several of the other outlying points in Fig. 4.10(a) also derived from 15-45 cm depth, it was considered that an improvement in the correlation between core RLD and minirhizotron PC might be obtained by dividing the core sample from that layer into two, enabling data from 15-30 cm to also be eliminated if necessary. This was therefore done in 1993, but as Fig. 4.10(b) shows, data points from 30-45 cm were also widely scattered and would thus have to largely be eliminated too in order to improve the correlation. There is obviously little value in combining the poor correlation from the 1993 experiment with that from 1992, and the reason why the former should have been so much worse isn't clear. One possibility is that the tube installation procedure in 1993 was not as good as in 1992, and that light transmitted along the tube/soil interface had an inhibitory effect on root growth adjacent to the some of the tubes.

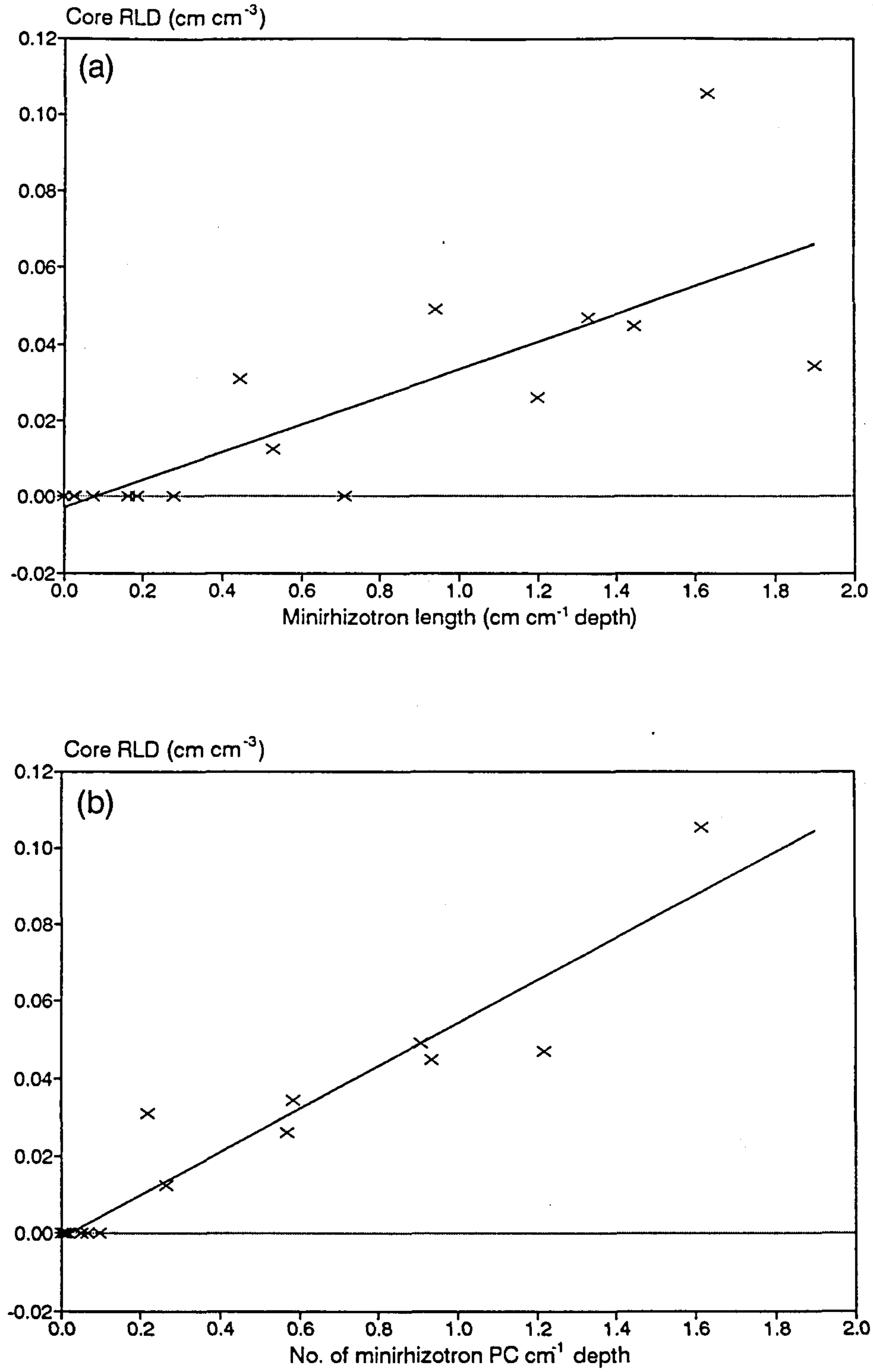


Fig. 4.8 The correlation between core root length density (RLD) and (a) minirhizotron root length and (b) the number of points of contact (PC) (both expressed per cm depth) at the 50 DAP sampling of the 1992 wheat experiment. Data points are means from three replicate plots and tubes (where available) at depth intervals below 15 cm. The equations of the linear regression lines are: (a) $y = 0.036x - 0.003$ ($r^2 = 0.62$) and (b) $y = 0.055x - 0.001$ ($r^2 = 0.91$).

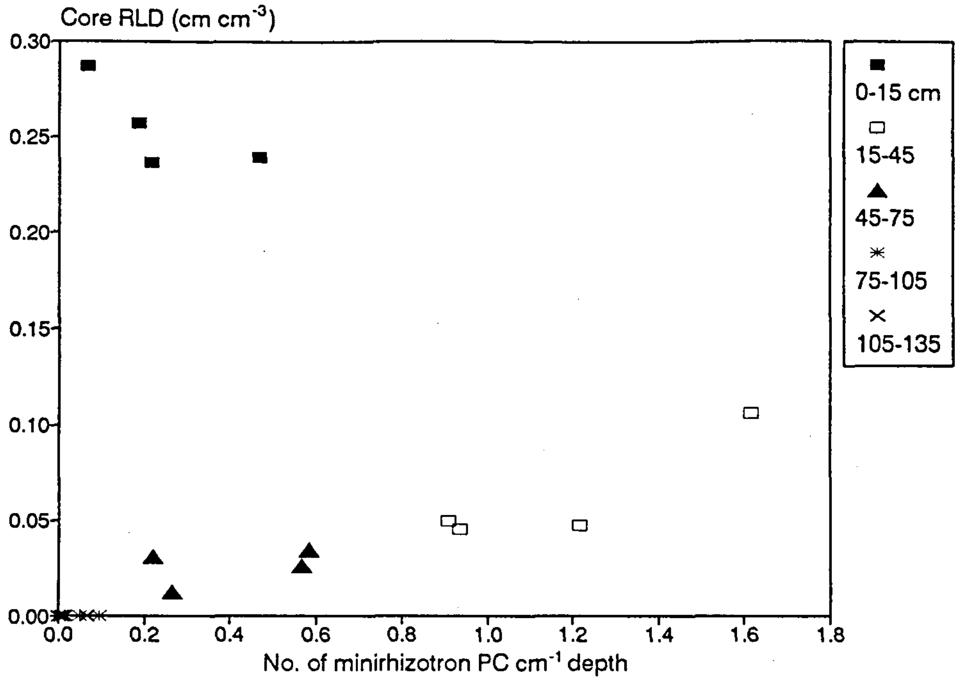


Fig. 4.9 The correlation between core RLD and the number of minirhizotron PC cm^{-1} depth at the 50 DAP sampling of the 1992 wheat experiment for all depth intervals.

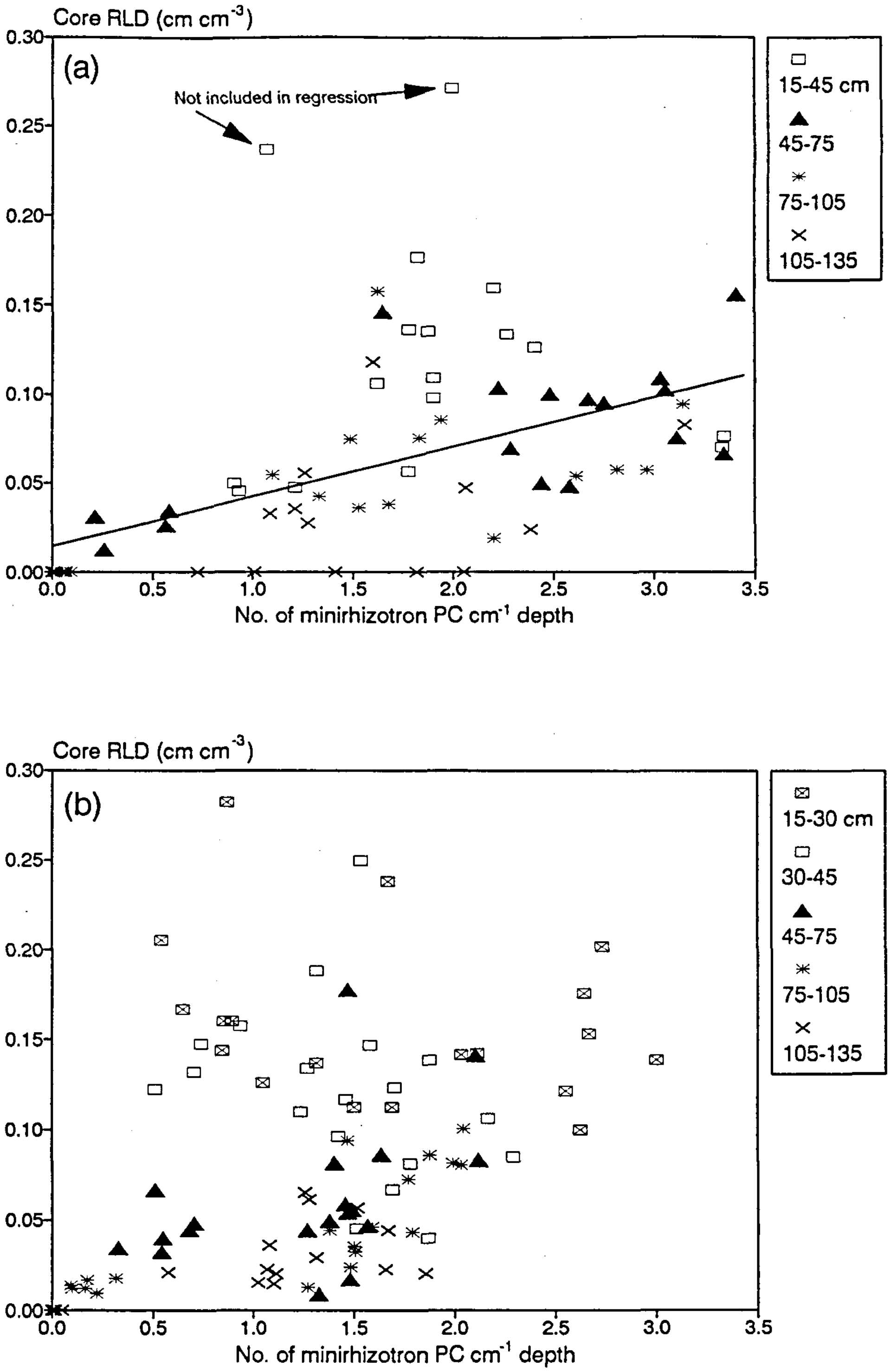


Fig. 4.10 The correlation between core RLD and the number of minirhizotron PC cm^{-1} for all sampling dates on which the two methods were used in both the (a) 1992 and (b) 1993 wheat experiments. The individual depth intervals (below 15 cm only) are shown. The equation of the linear regression line in (a) is $y = 0.028x + 0.014$ ($r^2 = 0.33$).

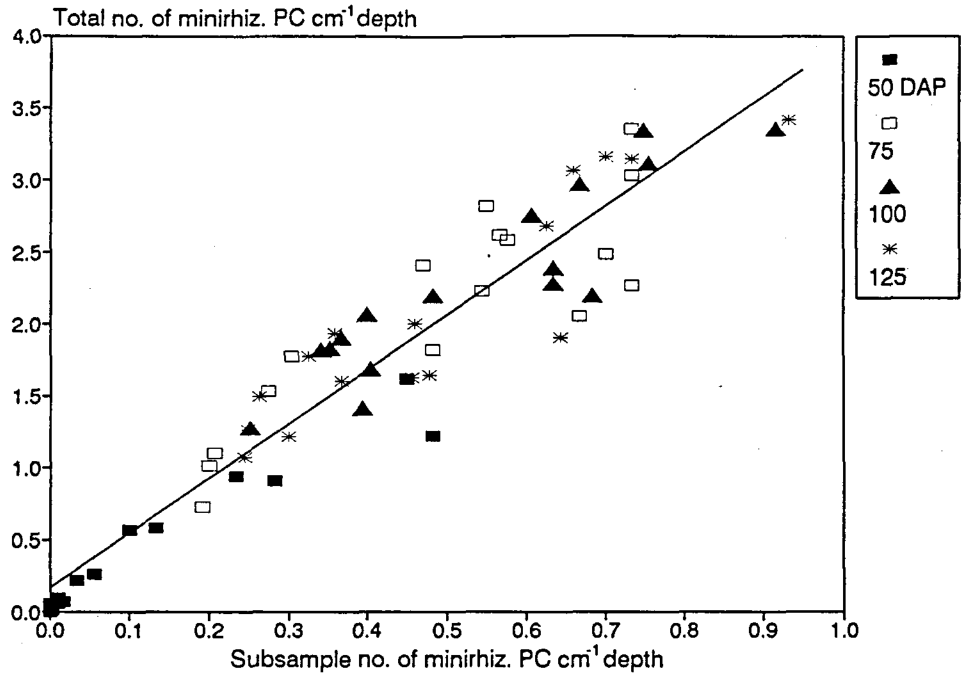


Fig. 4.11 The correlation between a subsample of the number of minirhizotron PC for the 6 images around the mid-point of each of the 15-45, 45-75, 75-105 and 105-135 cm depth intervals and the total number of PC, for four sampling times during the 1992 wheat experiment. The equation of the linear regression line is y = 3.77x + 5.21 (r^2 = 0.90).

Although considerably quicker than measuring root length, counting the number of minirhizotron PC in all 109 images along the full length of a tube is still a time-consuming process when six or more recordings have been made during the season from up to 30 tubes. To investigate whether only a "subsample" of each tube need be counted, from the 1992 data a subtotal for the 6 images around the mid-point of each of the 15-45, 45-75, 75-105 and 105-135 cm depth intervals was determined and plotted against the total (Fig. 4.11). An excellent correlation was found, indicating that it may be necessary to count PC in only 24 images per tube in order to compare estimates of root growth between different treatments.

4.3.2.2 Soybean

The correlations between core RLD and both minirhizotron root length and number of PC at the 50 DAP sampling of the 1991-92 soybean experiment are shown in Fig. 4.12. The data points are means from three replicate plots and tubes (i.e. 9 tubes, where available). As was found with wheat, tube position in the crop appeared to have no effect on the correlation, and thus the three tubes in each plot were treated as replicates. The number of PC again gave a better correlation with core RLD than length for data below 15 cm depth (the minirhizotron system once more greatly underestimating root growth in the surface layer). Fig. 4.13 shows the correlation between core RLD and the number of minirhizotron PC for all six sampling dates on which the two methods were used. Data points from the 0-15 cm layer have been omitted, but even if the widely scattered points from 15-30 cm depth are also eliminated the correlation is still very poor. In 1992-93, an inadequate number of core samples were taken which rendered any attempt to correlate data from the two methods impossible.

To ensure that the root growth observed by the minirhizotron camera is representative of that in the bulk soil, the interface between the upper surface of the tube and the soil should have no influence on it. Both gaps and compaction must be avoided, but the ease with which a good fit is obtained for the tube in its hole will depend largely on soil structure and texture. At the end of the 1991-92 soybean season (the first experiment in which the camera was used) a pit was dug next to two of the tubes in order to investigate how good a contact there was at the tube/soil interface and what happened to the roots after they grew on out of view of the camera. Contact between tube and soil was found to be very good, with few gaps, indicating that the installation procedure was successful. The tubes were installed at an angle to discourage root growth along their upper surface, and the excavation revealed that this method had been effective. Some of the roots which reached the tube grew on round it and continued following its under surface, but that does not influence the data obtained at the upper surface which can be considered representative of root growth in the bulk soil.

4.3.2.3 Comparison of methods

The correlations between core RLD and the number of minirhizotron PC for both wheat and soybean presented above are largely poor. This illustrates one of the difficulties involved when attempting to relate two methods of measuring a factor as variable as crop root growth. It has been assumed that the core samples gave the "true" values, but in both cases one must be sure that there is adequate replication in order to obtain representative values.

The inability of the minirhizotron system to provide a good estimate of root growth close to the soil surface is a major disadvantage. Another problem in a soil with a deep profile is that it is logistically impractical to obtain and install tubes longer than 2 m in order to observe the deepest roots. However, a major advantage of using minirhizotrons is that you can monitor the growth of the same roots over time, thus eliminating one of the sources of variability inherent in root studies. Although a good enough correlation between minirhizotron PC and core RLD was not obtained for either wheat or soybeans to allow PC data to be converted into quantitative RLD values, PC data can still be used to compare rooting profiles between treatments (see Chapter 7, section 7.2). The non-destructive nature of the technique also allows much greater detail concerning root development to be observed. For example, it would be extremely difficult to monitor changes in root diameter using the core method (see results in Chapter 7, section 7.2.1). Also the minirhizotron camera allowed N-fixing nodules on soybean roots to be clearly seen. They were first observed 6-7 weeks after planting in both seasons.

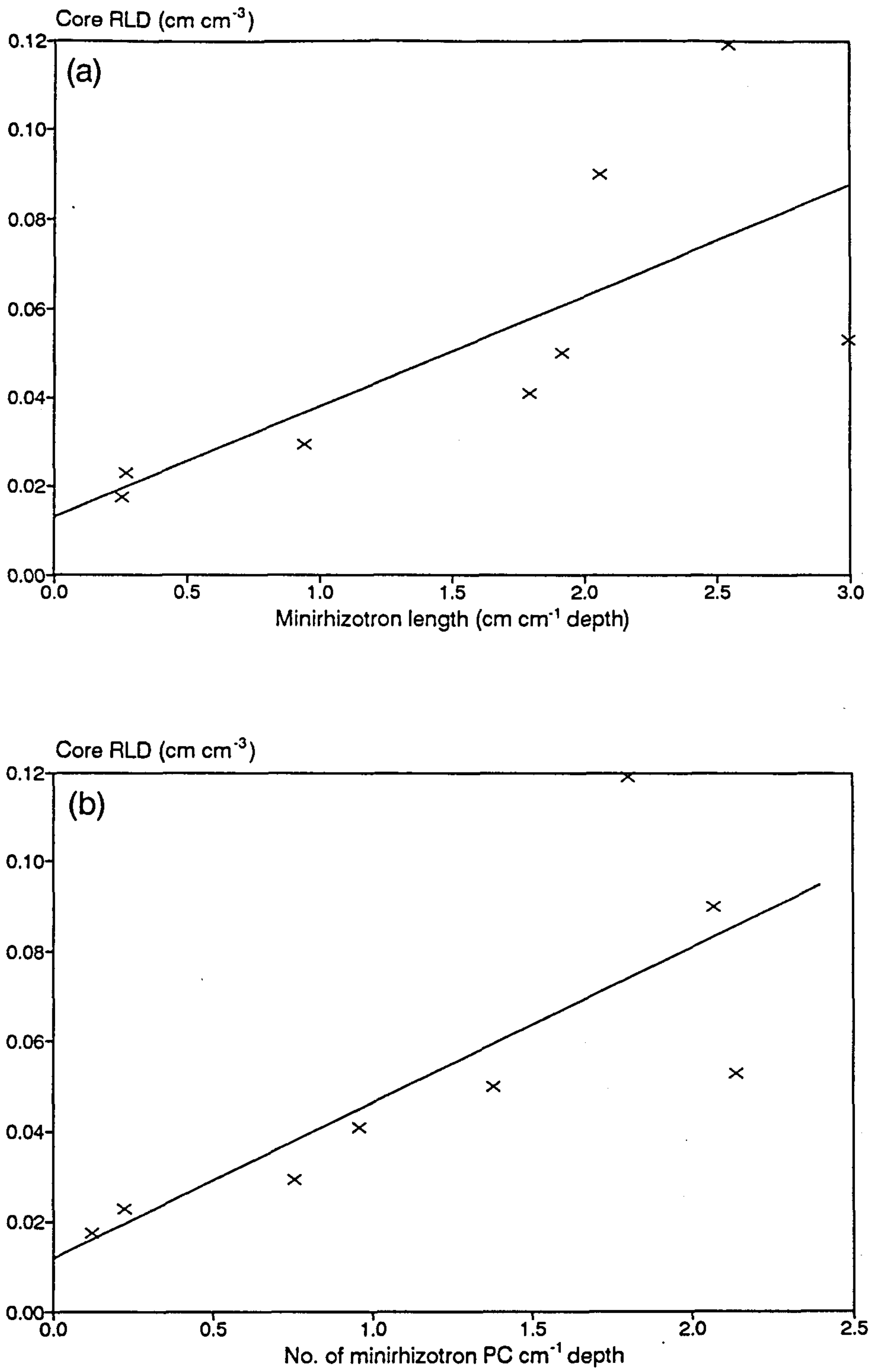


Fig. 4.12 The correlation between core RLD and (a) minirhizotron root length and (b) the number of PC (both expressed per cm depth) at the 50 DAP sampling of the 1991-92 soybean experiment. Data points are means from three replicate plots and tubes (where available) at depth intervals below 15 cm. The equations of the linear regression lines are: (a) $y = 0.025x + 0.013$ ($r^2 = 0.52$) and (b) $y = 0.035x + 0.012$ ($r^2 = 0.61$).

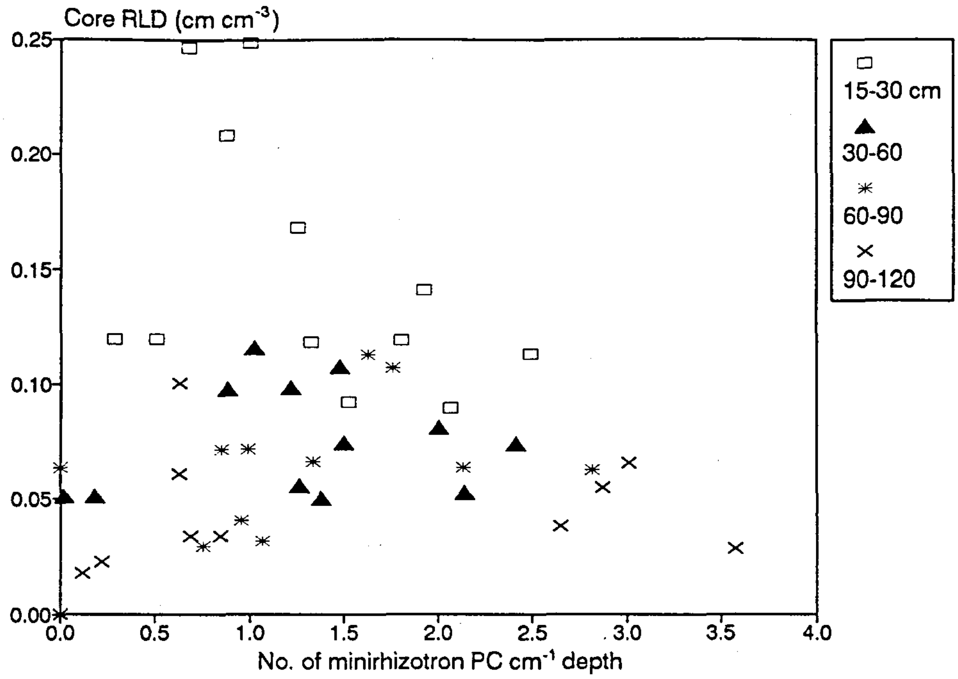


Fig. 4.13 The correlation between core RLD and the number of minirhizotron PC for all six soybean 1991-92 sampling dates on which the two methods were used. The individual depth intervals (below 15 cm only) are shown.

4.3.3 CONCLUSION

In the study of crop root growth both the minirhizotron and the soil core extraction methods have advantages and disadvantages. Minirhizotrons are unable to provide a good estimate of root growth close to the soil surface. It is also difficult to use them to observe very deep roots. The core method in theory allows you to measure root growth both near the surface and at depth. However, in practice problems often arise concerning the insertion and removal of the coring tube, particularly in dry soil. Once inserted when the soil is fairly moist, the minirhizotron tube remains there throughout the season, allowing non-destructive root growth measurements to be made whenever one desires. Other advantages of this system are that the growth of the same roots can be observed over time, and that root development can be studied in much greater detail than is possible with the destructive core method. One can even study the effect of water stress on root anatomy, e.g. the diameter of roots. Measurements such as this could be carried out at any time after the growth season has ended since all the root growth information has now been preserved on video tape. The relative merits of the two methods mean that they should really be used together in order to obtain a complete picture of crop root growth and development.

4.4 Core Break Technique for Estimating Rooting Density

This adaptation to the core sampling procedure (Bennie, Taylor & Georgen, 1987; Bland, 1989) allows rooting density to be estimated much faster than is possible when the roots have to be washed out of the soil before their length can be measured. It was first tried during the 1991 wheat and 1991-92 soybean experiments, and then used with more success in the 1992 and 1993 wheat experiments after some modifications had been made. Each core section was broken in half, the number of root ends visible on both exposed surfaces was counted and a mean of the two totals calculated. This mean was then expressed as root counts cm^{-2} of core cross-sectional surface area. Fig. 4.14 shows the correlation between core RLD and root counts for all sampling times combined, for both the 1992 and 1993 wheat seasons. The correlation coefficients of 0.81 and 0.71 respectively can be considered good enough to allow the core break technique to be used to predict RLD when a more rapid estimation of the root growth of a wheat crop is required.

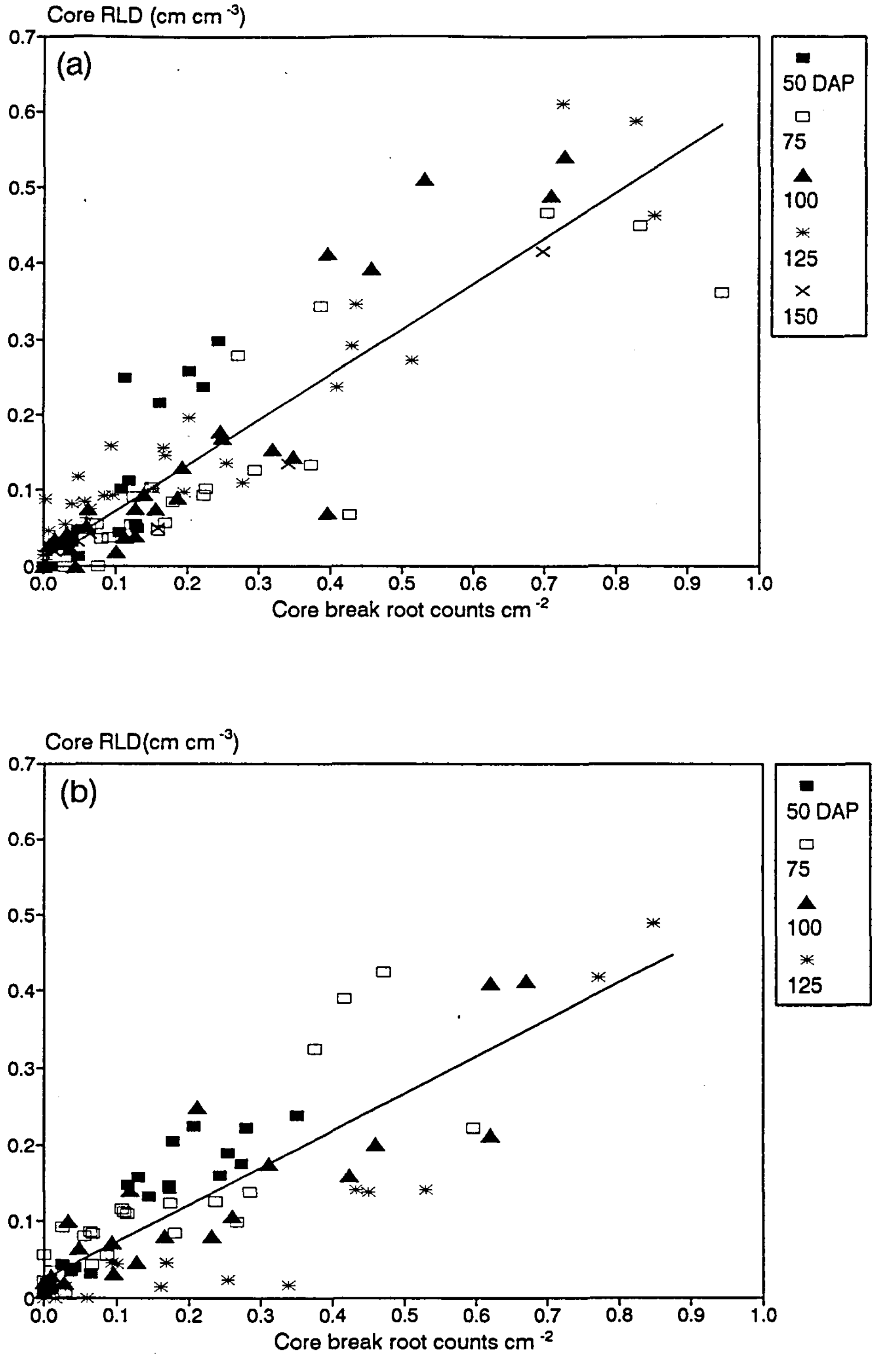


Fig. 4.14 The correlation between core RLD and root counts determined using the core break technique for all sampling times during the (a) 1992 and (b) 1993 wheat experiments. The equations of the linear regression lines are: (a) $y = 0.600x + 0.013$ ($r^2 = 0.81$) and (b) $y = 0.483x + 0.025$ ($r^2 = 0.71$). (Data points are means from 3 plots.)

4.5 Calibration of the SHOOTGRO Crop Model

The SHOOTGRO 4 crop growth model was developed for winter wheat in the USA by Dr. G.S. McMaster and co-workers (McMaster, Morgan & Wilhelm, 1992; McMaster, Wilhelm & Morgan, 1992; Wilhelm, McMaster, Rickman & Klepper, 1993). In order to use the model for spring wheat in this project it was necessary to calibrate it for South African conditions. This was done using historic field datasets, in collaboration with Dr. McMaster during his visit in 1993.

The following is a description of method used to calibrate SHOOTGRO. Further details on the use of the model are given in Chapter 10.

4.5.1 PHENOLOGY PARAMETERS

The basic approach in the PHENOL.FOR subroutine is to use the number of phyllochrons between various growth stages, except for grain-filling, which uses the number of growing degree-days (GDD). All thermal estimates are for optimal growing conditions. Water and nitrogen stress will alter the relationship, usually reducing the thermal requirement. For more detailed discussion of the approach see the SHOOTGRO 4 documentation (McMaster, Morgan & Wilhelm, 1992; McMaster, Wilhelm & Morgan, 1992).

4.5.2 THERMAL ESTIMATES

The PARAM.DAT file allows the user to change cultivar/species-related parameters without having to recompile the program. The following is a discussion of each parameter in the order they are read within the file. First comes the general miscellaneous values and coefficients, followed by the values and coefficients for stand establishment, vegetative processes, reproductive processes and phenology.

The thermal estimates between growth stages are inputs in the PARAM.DAT files. Because these estimates vary amongst cultivars and species, and phenology is an important driving variable in SHOOTGRO 4, careful attention to the thermal estimates needs to be given prior to running a simulation. Several default files are available as listed below. Each file has information at the top regarding the type of cultivar and species concerned.

(i) PARAMWW.DAT: This file contains estimates for a generic cultivar often used in the Central Great Plains, USA. Cultivars such as Vona or TAM 107, both semi-dwarfs, have similar thermal estimates.
(ii) PARAMSB.DAT: This file contains estimates for a generic cultivar grown at Mandan, North Dakota or St. Paul, Minnesota, USA. At this stage, very few studies have been carried out concerning these numbers, so we cannot put great confidence in them.
(iii) PARAMSA.DAT: This file contains estimates for a generic spring wheat cultivar grown in South Africa, related to SST86, which produces about 10 leaves.
(iv) PARAMSW.DAT: This file contains estimates for a generic spring wheat cultivar grown in the northern Great Plains of the USA, which produces about 8 leaves.

The PARAMSA.DAT file will be used as an example to illustrate the procedure for setting the thermal estimates. The steps are as follows:

1. Develop crop calendar dates for as many growth stages as possible. Particularly important stages are typical planting dates, jointing, anthesis and physiological maturity. For growth stages that one is uncertain about an alternative method can be used to estimate the approximate relationship with other growth stages. The default PARAM.DAT files have these relationships reflected in their thermal estimates. Also, assistance can be obtained from the SHOOTGRO 4 documentation and various manuscripts published concerning the model (McMaster, Klepper, Rickman, Wilhelm & Willis, 1991; McMaster, Morgan & Wilhelm, 1992; McMaster, Wilhelm & Morgan, 1992; Wilhelm *et al.*, 1993).

2. Determine if the crop calendar is for optimal or stressed conditions. The reason for this is that the OPARAM.DAT file should contain thermal estimates for optimal conditions, and that stress will alter the estimates within the model. If typical dryland conditions are used, then begin by adding 10% to the dryland estimates.

3. Two methods can be used to calculate the thermal estimates between growth stages:

   (a) The first is to use the default values provided in the PARAM.DAT file closest to your cultivar and conditions. After assembling the files needed for your simulation conditions, especially the weather file, then simply run the simulation and adjust the thermal estimates until the simulated growth stages occur on the same days as in the crop calendar. If only one year of weather data is used, one must be sure that it is somewhat "typical". It would be better to use long-term weather records for the calibration. However, one could omit data from years in which experiments were conducted for model validation purposes.

   (b) The second method is to determine the growing degree-days (GDD) between various growth stages using long-term weather records and the crop calendar, and then convert to the number of phyllochrons. If the phyllochron length is not known, one can assume values of 105 and 85 GDD for winter and spring wheat respectively. Again, if the crop calendar is not for optimal conditions, then add 10% to the estimated values. Put these thermal estimates at the end of the PARAM.DAT file, run the simulation, and modify the estimates as in the first method until predicted values match the crop calendar.

4. Only the thermal estimate from the start of anthesis (AS) to physiological maturity (M) does not use the number of phyllochrons as the measure of thermal time. Rather, AS to M is measured using GDD. A number of stages, such as the duration of anthesis (AS to AE) and the start of floret primordium initiation (FPIB), will rarely be changed by the user.

5. If any of the thermal estimates are changed, then the following parameters may need to be changed as well (see definition of terms in Table 4.1):

(a) If DRPA or TSPA thermal estimates are changed, then SPRATE must also be recalculated. To do this, add DRPA and TSPA and divide by the maximum number of spikelets expected under optimal conditions. For wheat this number should be about 25 spikelets per spike.

(b) If FPIBPA, DRPA, IEPA, JTPA or BOOTPA are changed, then FLOGRO must be recalculated by: (DRPA - FPIBPA + IEPA + JTPA + BOOTPA) divided by 10.

(c) If HEADPA or ANTSPA are changed, then FLODIE needs to be recalculated by adding HEADPA and ANTSPA, then dividing by 4 or 5. The concept is that about 10 floret primordia should be initiated on a central spikelet of wheat, and that floret primordia abortion should result in about 5 florets available for fertilization under optimal conditions. Therefore, FLOGRO and FLODIE are estimated to produce this pattern. If your cultivar never has 5 kernels in a central spikelet under optimal conditions, then increase FLODIE or decrease FLOGRO to reflect the number of kernels that you would expect.

(d) If ANTEPA is changed, then the GDDBFR and GDDFER parameters must change, although it is unlikely that the user will want or need to change ANTEPA. For GDDBFR, since there should be about 25 spikelets per spike under optimal conditions for wheat, this means there will be about 13 pairs of basal florets to potentially be fertilized. The number of basal pairs to be fertilized per phyllochron is calculated by dividing the 13 pairs by ANTEPA. Similarly for GDDFER, calculate FLOGRO and FLODIE by taking the number of florets per central spikelet that are available to be fertilized, subtract 1 and divide by ANTEPA.

Once these parameters are recalculated, run the model and look at the *.OUT file. At the bottom, if level 2 output is chosen, look at the spike "diagrams" at the end and adjust the estimates until the desired spike diagram is simulated.

Table 4.1 Definition of terms used in setting the thermal estimates in SHOOTGRO.

TERM	DEFINITION
ANTEPA	Parameter setting the number of phyllochrons between the beginning and end of anthesis
ANTSPA	Parameter setting the number of phyllochrons between the beginning of heading and the beginning of anthesis
BOOTPA	Parameter setting the number of phyllochrons between the beginning of jointing and booting
DRPA	Parameter setting the number of phyllochrons between single ridge and double ridge
FLODIE	Rate of floret primordia abortion within a spikelet
FLOGRO	Number of florets initiated within a spikelet under optimal conditions
FPIBPA	Number of phyllochrons between double ridge and flower primordium initiation
GDDBFR	Growing degree-days required to fertilize a pair of basal florets in spikelets under optimal conditions
GDDFER	Growing degree-days required for non-basal florets within a spikelet to be fertilized
HEADPA	Parameter setting the number of phyllochrons between the beginning of booting and heading
IEPA	Parameter setting the number of phyllochrons between double ridge and start of internode elongation growth stages
JTPA	Parameter setting the number of phyllochrons between beginning of internode elongation and jointing
SPRATE	Number of spikelet primordia initiated per phyllochron under optimal conditions
TSPA	Parameter setting the number of phyllochrons between double ridge and terminal spikelet growth stages

Chapter 5

WHEAT LEAF PHOTOSYNTHESIS

Photosynthesis supplies the building blocks for plant growth and development and for the final crop yield produced. Therefore it is vital for crop simulation models that the photosynthesis process and the factors affecting it are well understood. However, there is some difficulty in relating crop productivity to single leaf photosynthesis as the leaves in the canopy are of different ages, and each leaf has a unique position and is therefore exposed to a unique set of environmental factors. It is known that factors such as CO_2 concentration, radiation load, temperature and water status all affect leaf photosynthesis (Bunce, 1986). This increases the complexity of the system and makes extrapolation from single leaf measurements to canopy level almost impossible. In addition, the photosynthesis rate of a single leaf has been shown to alter with age for cotton (Wullschleger & Oosterhuis, 1990) and tomato (Bolanos & Hsiao, 1991). A detailed study on wheat was also needed where all the environmental and developmental factors are measured simultaneously with the photosynthetic rate of any one leaf. In this project the variation in photosynthesis characteristics of wheat leaves was investigated from leaf appearance through to senescence in a field environment under different water and nitrogen treatments.

Photosynthesis (P_N) is dependent on all prevailing environmental factors which affect leaf growth, including nutrient availability. As nitrogen is utilized in the P_N process, P_N rates will clearly be influenced by the N content of the leaf. However, one must also consider whether there are other limiting factors, such as water stress, which may have a greater effect on P_N, overriding that of N fertilization. Conflicting results have been reported in the literature for the relationship between leaf N content and P_N for several crops, perhaps as a result of the range of conditions that were encountered in the different projects (Yoshida & Coronel, 1976; Araus & Tapia, 1987; Wullschleger & Oosterhuis, 1990; Bolanos & Hsiao, 1991). Bolanos and Hsiao (1991) found that for field-grown tomatoes, P_N was dependent on N content irrespective of leaf age or water treatment. Wullschleger & Oosterhuis (1990) reported that a significant relationship between leaf N and photosynthesis was found only after the cotton leaves had unfolded. Evans (1983) concluded that a single relationship between P_N and N content for wheat flag leaves was justified. Similarly, Araus & Tapia (1987) found that there was a strong relationship between the P_N and N content per leaf area for wheat, although it appeared to be different for the leaf sheath and the leaf blades. A second objective of this study was to investigate the relationship between N and P_N for wheat leaves at different insertion levels in the crop canopy to compare possible changes during the season.

5.1 Development Patterns of P_N and Leaf Biomass and N Content

5.1.1 MATERIALS & METHODS

Photosynthesis measurements were made in the physiology plots of the 1991, 1992 and 1993 wheat experiments using a LICOR LI6200 portable single leaf system (see Chapter 4, section 4.1). Measurements were made at 3 to 4 day intervals from leaf tip appearance until senescence. In 1992 and 1993 alternate leaves, numbers 3, 5, 7 and 9 (the flag leaf), were used, whilst in 1991 only leaf 6 and the flag leaf were measured. Following the P_N measurement the leaf was removed from the plant for growth analysis and determination of N content. Leaf samples were dried in an oven at 60 °C for 48 h. Leaf N content was measured by the Kjeldahl method, on the small section of the leaf that had actually been in the photosynthetic chamber.

5.1.2 RESULTS & DISCUSSION

Due to the morphology of a monocotyledonous plant like wheat, the leaves already have a considerable area by the time they appear in the open. However, it was impossible to measure the P_N of the leaves while still enclosed in the leaf sheath and before they were unfurled. Measurements began on the flag leaf as soon as there was sufficient leaf blade protruding from the whorl to attach the chamber (approximately 6 cm). Thus the initial increase in P_N is not clearly seen for leaf 6, although all treatments except W1N0 did show a slight increase between the first and second readings (Fig. 5.1(a)). The eye-fitted curve for the flag leaf is much clearer showing the increase as the leaf was growing and unfurling (Fig. 5.1(b)). On the W5N3 treatment, over the first 3 measurement dates P_N increased by more than 10 μmol m^{-2} s^{-1}. The P_N then reached a plateau which was maintained for only a few days in leaf 6 but for at least 20 days in the flag leaf. Following the plateau, P_N declined as leaf senescence took place.

5.1.2.1 P_N and Biomass Variations with Leaf Age

The flag leaf showed an increase in P_N with time after appearance of the leaf tip, then a plateau followed by a steady decline to negligible P_N at physiological maturity (Walker & Oosterhuis, 1992; Oosterhuis & Walker, 1992). Fig. 5.2 presents single leaf biomass data to illustrate the growth of the leaves during the time period of the photosynthesis and N measurements. Leaf 6 did not increase in dry mass during this period, as the measurements only began after the ligule had appeared and expansive growth was completed (Fig. 5.2(a)). There were no differences in the mass of leaf 6 between the different treatments. In contrast, the treatment effects on leaf size were clearly visible for the flag leaf (Fig. 5.2(b)). The dry mass of the well-watered, optimal N treatment was almost double that of the well-watered, zero N treatment. The dryland treatments were again similar, although N3 was slightly larger than N0. Mean final yields were 7.66 and 3.24 t ha^{-1} for the well-watered N3 and N0 treatments and 2.74 and 2.41 t ha^{-1} for the dryland N3 and N0 treatments respectively. The compounding effect of the larger leaf biomass and a higher P_N for the well-watered optimal N treatment resulted in a higher final yield.

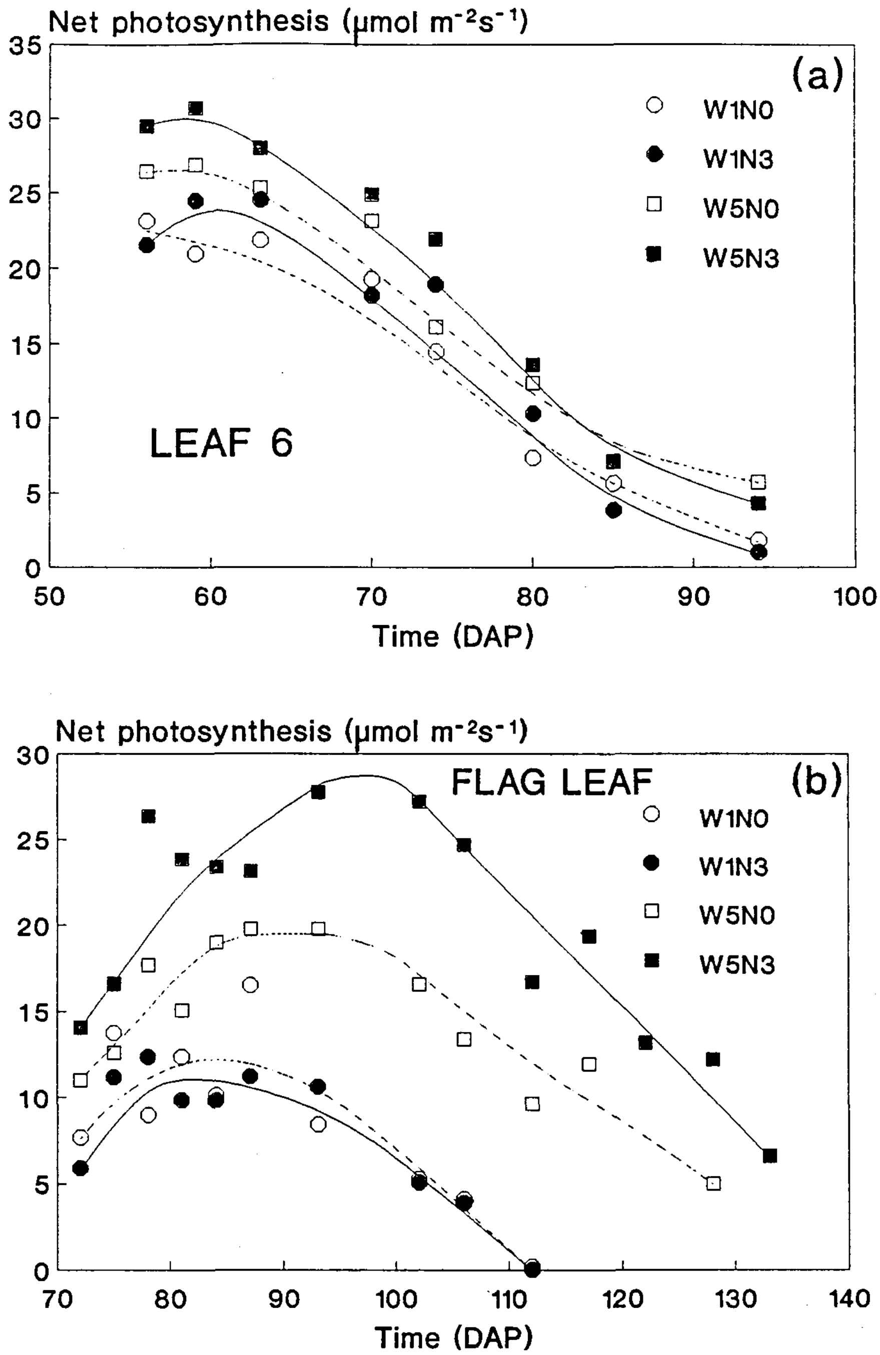


Fig. 5.1 Wheat 1991 net photosynthesis of (a) leaf 6 and (b) the flag leaf for two well-watered treatments (W5) at zero N (NO) and optimal N application (N3) and two dryland treatments (W1) at the two levels of nitrogen application. (Eye-fitted curves.)

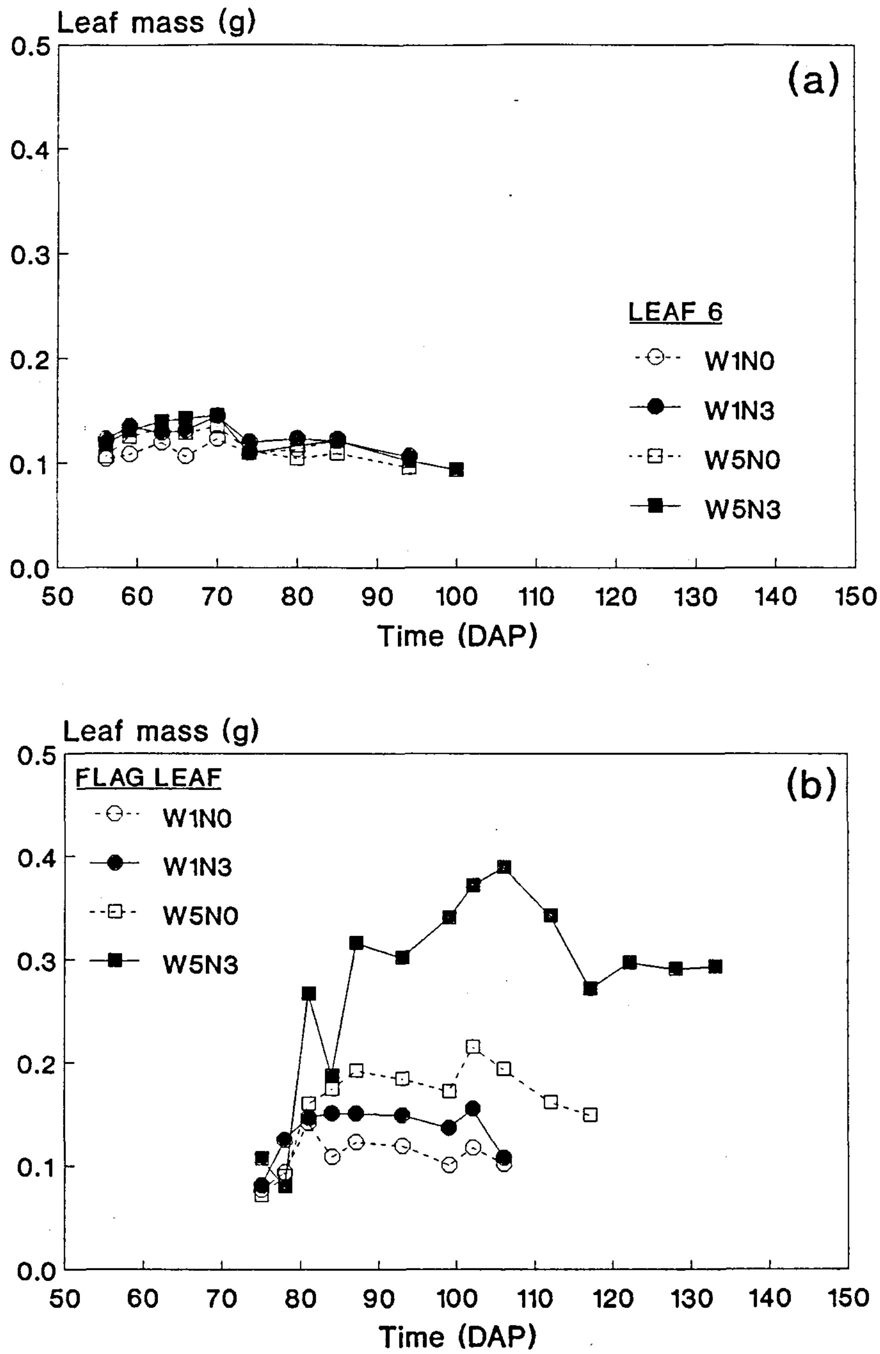


Fig. 5.2 Wheat 1991 single leaf biomass for (a) leaf 6 and (b) the flag leaf at well-watered (W5) and dryland (W1) irrigation treatments and optimal (N3) and zero (N0) nitrogen application treatments.

5.1.2.2 N Content Variation with Leaf Age

The leaf N content (%) declined linearly with age for both the flag leaf and leaf 6 under well-watered conditions in both N treatments (Fig. 5.3(a)). The flag leaf N content at leaf appearance was slightly lower than that of leaf 6, being 5.8 and 6.8 % respectively for the high N treatments and 3.9 and 5.3 % for the low N treatments. The decline in leaf N content of the flag leaf with age was slower than that of leaf 6. This could be expected as leaf 6 was lower in the crop canopy, whereas the flag leaf was the final leaf and so had a longer duration. The effect of N application on leaf N content was large under well-watered conditions. The plants that received an N application had a leaf N content consistently 1.9 % higher than in the N0 treatment, irrespective of the leaf age or leaf number (Fig. 5.3(a)). Under dryland conditions, there were no differences in the leaf N content for the two N application levels (Fig. 5.3(b)). Leaf 6 showed a decline in N content from 6.3 % immediately after leaf appearance, but thereafter a plateau was reached at about 4 %. In contrast, the flag leaf N content did not decline with age. Average values were 3.7 % for the N3 treatment and 3.1 % for the N0 treatment, but this difference was not significant. Under well-watered conditions, the N content of both leaves was greater in the high than in the low N treatment and also greater than in both dryland treatments. For the well-watered and high nitrogen application treatment, the peak was at approximately 6 % for the flag leaf and 7 % for leaf 6 at leaf emergence, compared to maximums of 4.5 % and 6.5 % respectively for the dryland treatments.

As expected the N content of the two treatments that had no applied nitrogen were very similar, regardless of the water supply, at between 3 and 4 %. The data suggest that the effect of different irrigation levels on leaf N content was greater than the effect of N application levels. This was due to the controlling effect of available water on the plant physiological system.

5.2 Relationship between P_N and N Content

The 1991 data for the flag leaf P_N and N content showed a large spread from 2-6 % for N content and 5-30 μmol m^{-2} s^{-1} for the photosynthetic rates (Fig. 5.4(a)). The data for the dryland treatment was clumped between 2.5 and 4 % N, with P_N less than 13 μmol m^{-2} s^{-1} and no significant differences due to the overriding effect of severe water deficit. Therefore, excluding the dryland data from the linear regression analysis for the flag leaf, there was a linear correlation between P_N and leaf N content (slope = 3.54 μmol m^{-2} s^{-1} $(\%N)^{-1}$; r^2 = 0.42) for the well-watered treatments. This large spread in the data has been reported in other studies of wheat flag leaves (Evans, 1983; Araus & Tapia, 1987).

In leaf 6, P_N was linearly correlated with N content for all treatments (Fig. 5.4(b); slope = 4.59 μmol m^{-2} s^{-1} $(\%N)^{-1}$; r^2 = 0.56). This data is in agreement with Evans (1983) who showed that there was a constant relationship between N content and P_N regardless of environmental or stress factors. As leaf 6 grows in the middle of the vegetative development phase it serves as a representative leaf for the whole crop canopy. During the initial stages of leaf 6 growth the water stress was beginning to develop, and during the later stages it suffered from mild stress. Therefore, leaf 6 appears to be a good leaf to consider for the assessment of leaf N content before deciding whether to apply a nitrogen top-dressing.

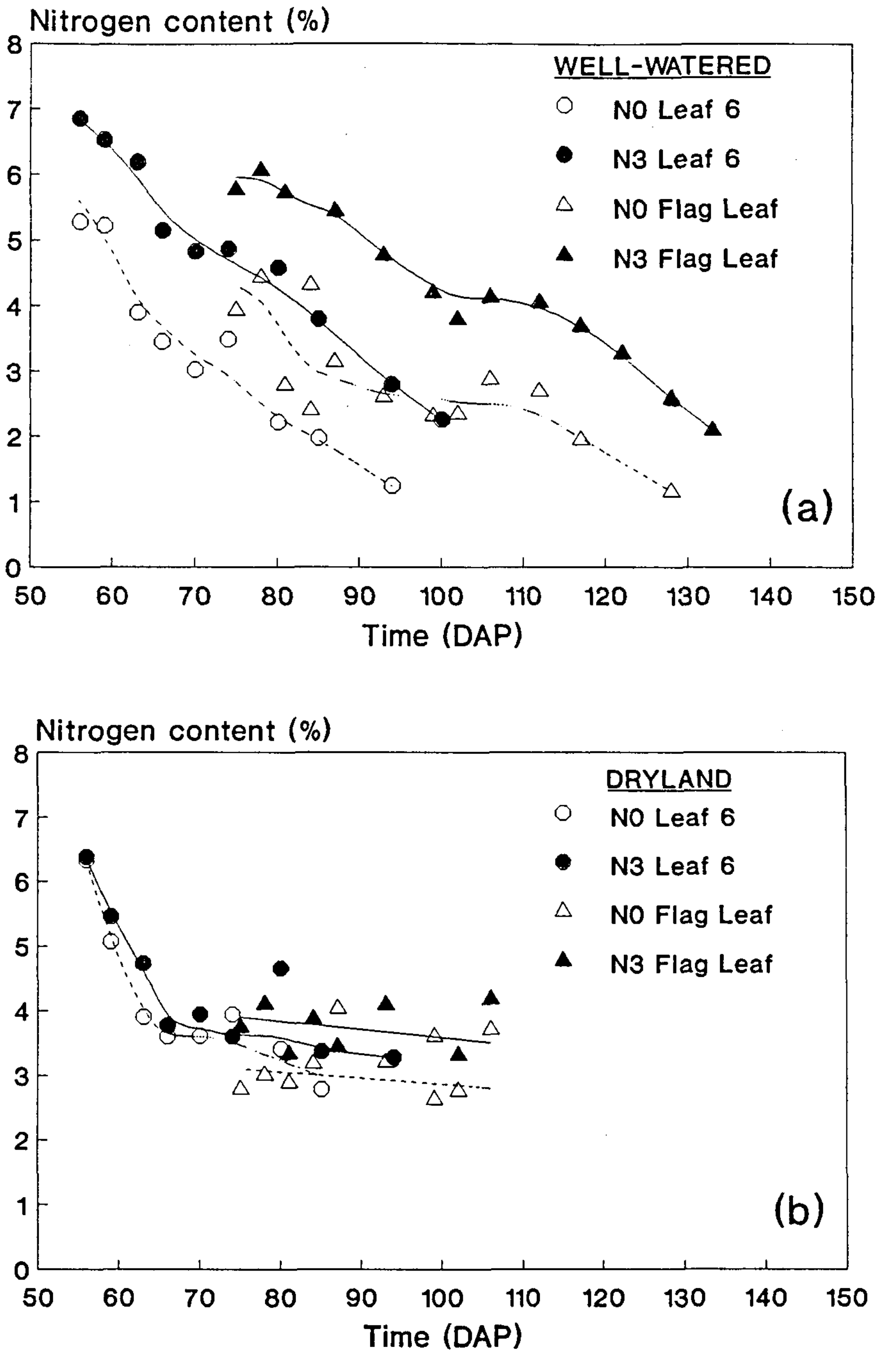
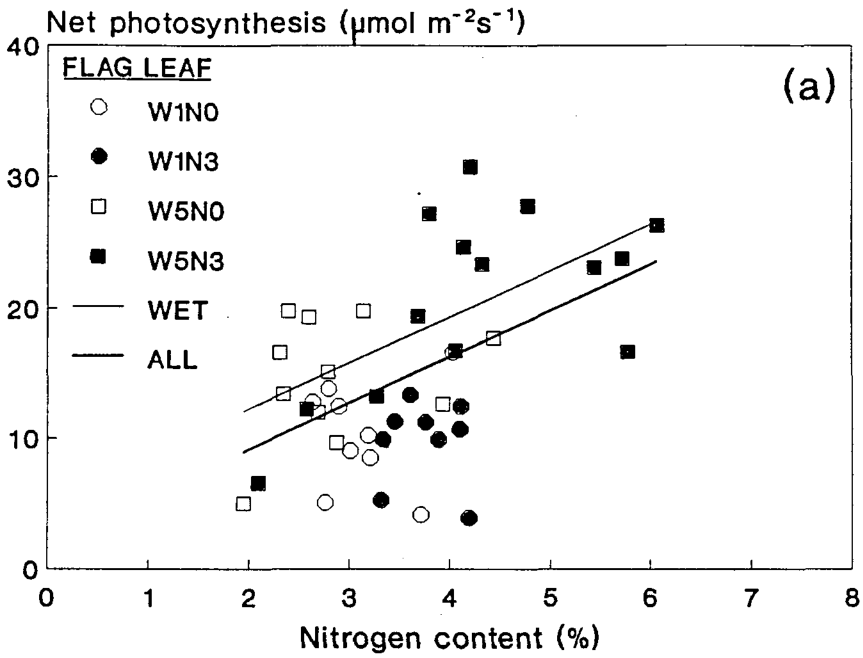


Fig. 5.3 Wheat 1991 N contents for leaf 6 and the flag leaf grown under (a) well-watered and (b) dryland conditions at optimal (N3) and zero (N0) N application levels. (Eye-fitted curves.)



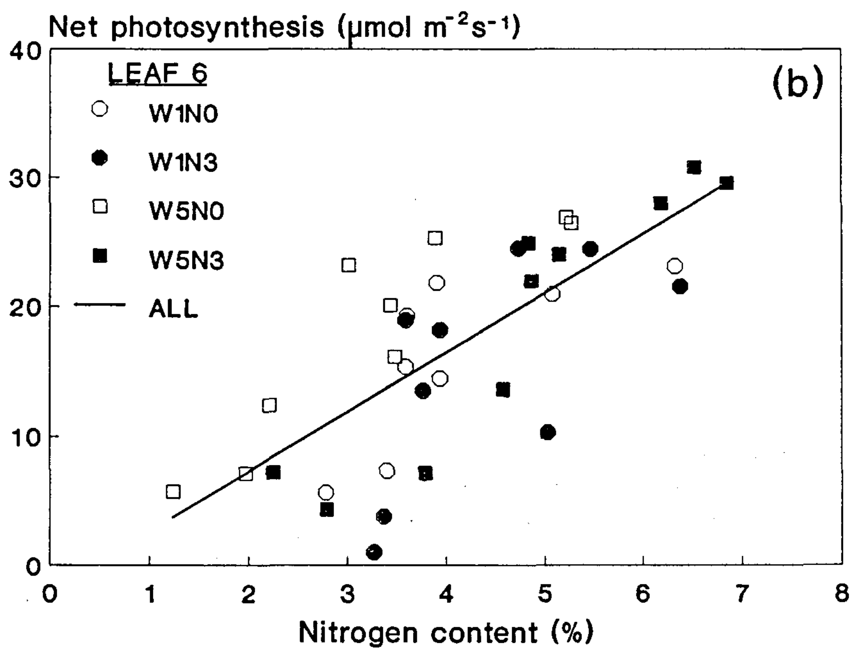


Fig. 5.4 Relationship between wheat 1991 net photosynthesis and leaf N content for (a) the flag leaf and (b) leaf 6 grown under both well-watered (W5) and dryland (W1) conditions at optimal (N3) and zero (N0) nitrogen application levels. (a) The equation of the line for all the points is $P_N = 2.02 + 3.55(\%N)$ ($r^2 = 0.26$), and for W5 only is $P_N = 5.14 + 3.54(\%N)$ ($r^2 = 0.42$).
(b) The equation of the line is $P_N = -1.90 + 4.59(\%N)$ ($r^2 = 0.56$).

5.3 Effect on P_N of Water and Other Factors

5.3.1 WATER AND NITROGEN STRESS

Although the trend of the decline in P_N with declining leaf N content for leaf 6 was the same for all treatments, there were small differences between them. The decline stretched over about 30 days, which coincides with the period of the flag leaf P_N plateau. The well-watered high nitrogen treatment (W5N3) had a higher P_N rate than the corresponding low nitrogen treatment (W5N0), and the two dryland treatments had even lower maximum P_N values.

The treatment differences were accentuated for the flag leaf. The average plateau value of P_N for the W5N3 treatment was 27 μmol m^{-2} s^{-1}, while for the W5N0 treatment it was about 8 μmol m^{-2} s^{-1} or 30 % lower. These differences were also maintained through the declining P_N period. The water stress effect was even greater than that of low nitrogen, and the dryland plots attained a P_N plateau value only about 45 % of that of the well-watered, high nitrogen plots. Under dryland conditions there was little or no effect of nitrogen application and the two treatments maintained similar plateau values. The slope of the dryland treatments during the decline period was similar to that of leaf 6 and about twice as steep as that of the well-watered treatments.

The adequate water supply prolonged the leaf area duration by about 30 days (see Chapter 7, Fig. 7.2(a)), and therefore the photosynthesis was also maintained during this period. There was a substantial difference between the maximum leaf area index (LAI) that was obtained on the W5N3 treatment compared to the other treatments. The LAI on the W5N0 treatment had a maximum value comparable with the dryland treatments; however, the leaf area duration of this treatment was prolonged slightly after the dryland treatments had already gone into senescence.

5.3.2 LEAF WATER USE EFFICIENCY

Water use efficiency (WUE) gives an assessment of the dry matter production per unit water consumption by the plants. If the photosynthesis data are used in conjunction with transpiration, also measured by the LICOR system on a single leaf basis, a leaf-scale instantaneous WUE can then be calculated. The single leaf transpiration measurements for the flag leaf are shown in Fig. 5.5(a). As there was variation due to the daily weather conditions, eye-fitted curves were drawn through the points. The overall trend was that the transpiration of the leaf increased with age, until about 110 DAP for the well-watered treatments, and then showed a steady decline as the leaf senesced. This peak in transpiration occurred 3 weeks after the leaf P_N had begun to decline. The transpiration of the N0 treatment was about two-thirds that of the W5N3 treatment. No differences were detected between N levels under the dryland treatments, both having a transpiration of about a third that of the W5N3 treatment. The WUE declined as the leaves aged (Fig. 5.5(b)), which appears to be largely due to the low transpiration rates during the early leaf expansion period resulting in a high WUE. After the P_N plateau had been reached the WUE declined rather rapidly, as this was the period when the transpiration rate was steadily increasing.

5.3.3 PLANT WATER STATUS

The water status of the wheat plants was monitored by routine measurements of midday leaf water potential. The development of water stress through the 1991 growing season is shown in Chapter 7, Fig. 7.2(c). Differences between the well-watered and dryland treatments were first detectable about 65 DAP, which is during the period when leaf 6 P_N was being measured. This was just prior to the start of the P_N measurements on the flag leaf, and this can help to explain the P_N differences between the treatments even during those first few days of measurement. By the time P_N reached its maximum value on about 90 DAP, the water stress was well developed, showing a leaf water potential difference of about -1 MPa.

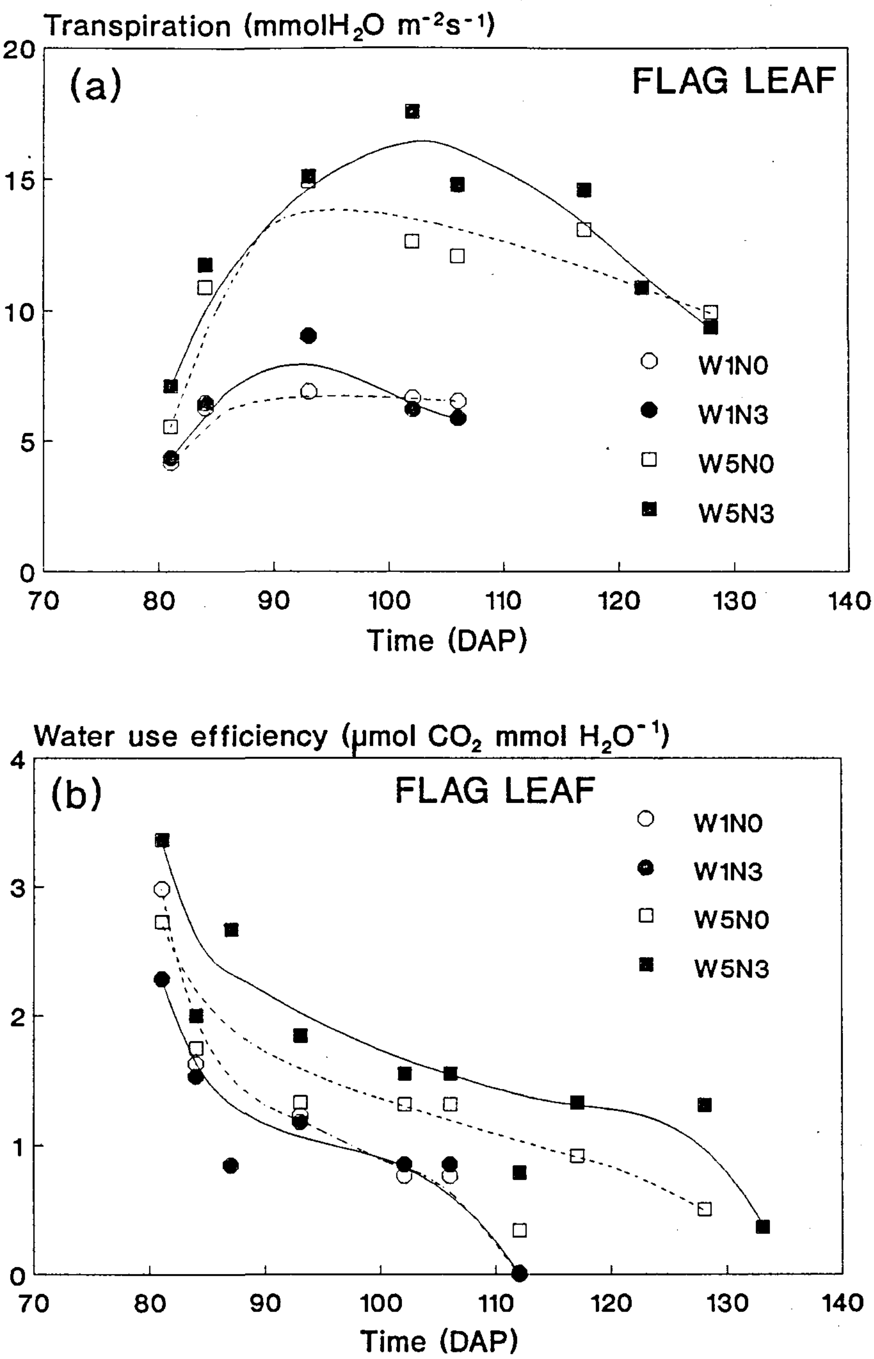


Fig. 5.5 Wheat 1991 (a) single leaf transpiration rates and (b) water use efficiency for the flag leaf.

5.3.4 STATISTICAL ANALYSIS

As photosynthesis is known to be influenced by various environmental and plant factors, results from each of the three years were analyzed using the GENSTAT Forward Selection Stepwise Regression procedure to characterize and describe the effect of the potential influences. The additional data recorded by the LICOR system (conductance, internal CO_2 concentration, transpiration rate, PAR and leaf temperature) were used, together with the measured leaf nitrogen contents. Data from the routine measurements of leaf water potential were also included in the analysis, as were leaf number and age, and time after planting. There were 931, 1207 and 1195 values in the 1991, 1992 and 1993 datasets respectively.

Firstly, a Principal Components Analysis was conducted to check for independence of the x variables. One variable from any dependent pair must be eliminated from the dataset before performing the Stepwise Regression. As expected, in all three years it was found that the two different ways of expressing leaf stomatal conductance to water vapour, on a molecular basis in μmol m^{-2} s^{-1} and as a velocity, were co-dependent. The latter was therefore omitted. Leaf number and days after planting were also found to be linked so, as leaf age had been included, the DAP variable was excluded.

The Forward Selection Stepwise Regression procedure selects x variables in the order of their degree of influence on y (photosynthesis). It picks the most important first, and then continues adding variables in the regression equation until there is no further improvement to the r^2 value, when the procedure stops. Table 5.1 gives the order of selection of variables, the % variance they accounted for and the regression coefficients for each of the three years. Although the total % variance accounted for (i.e. the final r^2 value) is >60 % in all three years, there was little consistancy in terms of the order of selection of the variables. In 1991 leaf temperature was selected was the variable with the greatest influence on P_N, with the negative regression coefficient indicating that as temperature increased the stomata closed and therefore photosynthesis declined due to the decrease in CO_2 availability. Leaf number also had a major effect, with the positive coefficient indicating that P_N was greater, the higher the leaf position on the plant. In 1992 the age of each leaf was the most important factor, having a negative effect on P_N. In 1993 stomatal conductance to water vapour had by far the greatest effect, accounting for 47 % of the variation in P_N. As with leaf temperature in 1991, the negative regression coefficient can be explained by the fact that if the stomata are closing then less CO_2 will be available for photosynthesis.

5.4 Conclusion

The overall trend in the wheat experiments showed a correlation between the nitrogen status of a leaf and its net photosynthesis, as N is essential for the photosynthetic process. The relationship was more marked for leaf 6 than for the flag leaf, where the effect of N application was overridden by severe water stress.

There were definite detectable differences in P_N between the different leaves on a plant. At a single insertion level the P_N increased as the leaf expanded and then declined as the leaf aged. The negative effects of water stress on P_N were larger than those due to lack of N, and under dryland conditions the addition of N did not appear to alleviate the stress due to drought. The lower P_N rates led to slower leaf growth and poor crop canopy cover, resulting in a lower final yield.

Table 5.1 Results from the Forward Selection Stepwise Regression analysis of the 1991, 1992 and 1993 photosynthesis data, showing the order of selection and percentage variance accounted for by each variable in its effect on photosynthesis, and the regression coefficients.

VARIABLE	1991			1992			1993		
	ORDER	% VAR.	COEFF.	ORDER	% VAR.	COEFF.	ORDER	% VAR.	COEFF.
Conductance	3	6.6	13.63	3	4.8	-0.38	1	47.4	-0.050
Internal CO_2 conc.	4	7.5	-0.074	4	14.1	-0.10	3	3.1	-0.061
Leaf age	-	-	-	1	24.9	-0.16	2	6.5	-0.053
Leaf N content	5	0.8	0.75	2	9.0	0.16	-	-	-
Leaf number	2	21.6	0.96	5	3.0	-0.56	7	3.4	1.32
Leaf temperature	1	38.2	-0.72	8	3.4	-0.86	5	2.1	-1.00
Leaf water poten.	6	0.7	0.0021	9	0.3	0.0012	8	0.2	0.0010
PAR	-	-	-	6	1.7	0.0015	4	2.6	0.0022
Transpiration rate	-	-	-	7	0.6	0.98	6	4.0	0.96
CONSTANT			40.82			62.83			36.45
FINAL r^2			0.75			0.62			0.69

Chapter 6

WATER FLOW IN THE SOIL-PLANT-ATMOSPHERE SYSTEM

One of the original objectives of this project was to investigate resistances to water flow in the soil-plant-atmosphere continuum. The atmosphere provides the driving force for transpiration from the leaves, which have a high water content compared to the dry air. The soil is the source of water for the plant, and that water must find the path of least resistance through the plant before evaporating into the atmosphere. Water flow in the soil-plant-atmosphere system can be described using the Ohms law analogue, where water flow is equal to the water potential gradient divided by the resistance between the two points used for the water potential measurements. Some of the data necessary for this study was collected routinely (e.g. midday leaf water potential), but a method of accurately measuring the rate of water flow through a single stem was required. In collaboration with Dr. Y. Cohen of the Institute of Soils and Water, Volcani Center, Israel, the heat pulse technique was used (see technical and calibration details in Chapter 4, section 4.2).

6.1 Use of the Heat Pulse Technique to Measure Transpiration, and Comparison with Methods of Calculating Evapotranspiration

The successful adaptation of the heat pulse system for use with the delicate stem of a wheat tiller (described in Chapter 4, section 4.2) was a major achievement. However, the technique is not an easy one to use, particularly in a field crop where the delicate probe connections are susceptible to the potentially disruptive influence of *inter alia* irrigation, rain and wind. It is readily susceptible to failure and inaccuracies unless carefully monitored. On an agronomic scale it should thus only be considered as a research technique. However, in this respect it does allow transpiration to be distinguished from the total evapotranspiration of a crop, and has the advantage over lysimeter studies of being portable so that measurements can be made anywhere in the crop and at any site. The technique was used during both the

1992 and 1993 wheat experiments and the 1992-93 soybean experiment to compare the transpiration rates of plants grown under different treatments. The results were then compared with daily evapotranspiration calculated from meteorological data using both the Penman-Monteith and Priestley-Taylor equations.

6.1.1 MATERIALS & METHODS

6.1.1.1 Wheat

In 1992, once the lysimeter calibration had been completed the heat pulse system was moved to the main experiment. Five probes were installed in representative main tillers in a well-watered (W5) physiology plot and five in a dryland (W1) plot (both with optimum nitrogen, N3). Data were recorded continuously from 108 to 114 DAP, when plants in the W1 plot senesced. Five probes were then installed in an optimum nitrogen (N3) treatment and five in a zero applied nitrogen (N0) treatment (both well-watered, W5), and data recorded from 117 to 141 DAP. Node diameters were measured at the end of both periods, and transpiration rate ($mm^3\ s^{-1}$) was calculated from vA (less the default zero value) using the predetermined wheat calibration coefficient (Chapter 4, section 4.2.2.1, equation 4.3). The volume of water transpired every 30 min was determined and these totals summed over 24 hours and expressed as $l\ d^{-1}$. The density of mature heads at final harvest in each plot was used to convert this volume into $mm\ d^{-1}$ in order to make comparisons with calculated evapotranspiration. A similar study was undertaken in 1993, with data obtained from W5N3 and W1N3 plots between 94 and 114 DAP and from W5N3 and W5N0 plots between 133 and 146 DAP.

6.1.1.2 Soybean

In 1992-93, heat pulse probes were installed in five representative plants in a 21 d irrigation frequency plot under the rain shelter, and five in an adjacent 3 d plot outside the shelter (both cv. Hutton). Data were recorded continuously from 89 to 118 DAP. Stem diameters were measured at the end of this period, and transpiration rate ($mm^3\ s^{-1}$) was calculated from vA (less the default zero value) using the predetermined soybean calibration coefficient (Chapter 4, section 4.2.2.2, equation 4.4). The volume of water transpired every 30 min was determined and these totals summed over 24 hours and expressed as l d^{-1}. Plant density at final harvest in each plot was used to convert this volume into mm d^{-1} in order to make comparisons with calculated evapotranspiration.

6.1.2 RESULTS & DISCUSSION

6.1.2.1 Treatment differences

6.1.2.1.1 Wheat

Transpiration rates (l d^{-1}) from the water and nitrogen treatment comparisons of 1992 and 1993 are presented in Figs 6.1 and 6.2 respectively. Fig. 6.1(a) shows that there was a significant overall difference in transpiration rate between the well-watered and dryland treatments (GENSTAT ANOVA: $p = 0.020$). This would be expected since the dryland plants were close to senescence when those measurements were made. Fig. 6.1(b) indicates that until the plants senesced at the end of the measurement period, those in the zero N treatment were transpiring at a higher rate than those in the optimum N treatment. However, wide variation amongst the three replicate tillers in each treatment resulted in an overall difference that was not significant. Two of the five probes per treatment were not functioning properly at this time, and even when all five are working this limitation in the number of replicate plants per treatment is still a major problem when statistically significant differences are required. Fig. 6.1(b) also shows the decrease in transpiration as the plants aged. The rapid drop on certain days can be attributed to cloud cover. Sharp increases, such as at 110 DAP in Fig. 6.1(a), are usually the result of irrigation on the previous day. In 1993 the probes were installed in the W5N3 and W1N3 plots earlier than in 1992. Fig. 6.2(a) shows that the transpiration rate of the two treatments diverged with time from an initially non-significant to a latterly significant difference. The probable explanation for this would be a combination of the dryland plants senescing and a steady increase in air temperature during this period. The large significant increase (GENSTAT ANOVA: $p = <0.001$) in the transpiration rate of the W5N3 plants between 137 and 142 DAP (Fig. 6.2(b)) coincided with a period when maximum air temperatures of over 30 °C were recorded. However, transpiration in the W5N0 treatment would have been expected to increase also but did not. There is some doubt as to the accuracy of the W5N3 data presented in Fig. 6.2(b). Due to installation problems no plastic supports were used on the stems of those 5 tillers. The absence of this insulation appeared to lead to some unexpectedly high heat velocities during the day, and some low values were even recorded during the night when zero is normally found with wheat.

Since meteorological factors such as air temperature and radiation are the driving forces for evapotranspiration they are strongly correlated with transpiration rate. However, when such factors are equal, the difference in rate between plants in two treatments is likely to be chiefly influenced by the total leaf area of each plant. A plant under water stress conditions will produce a smaller leaf area than a well-watered plant, which will result in a smaller surface area from which water can be lost to the atmosphere. The extent to which the difference in transpiration between wet and dry treatments in Figs 6.1(a) and 6.2(a) was an effect of leaf area was therefore determined. On the days when leaf area measurements were made in the W5N3 and W1N3 plots, the expected reduction in transpiration from W5 to W1 was calculated based on the % difference in the leaf area of the main tillers between the two treatments. These points are also plotted in Figs 6.1(a) and 6.2(a) and indicate that virtually the entire decrease in transpiration in the dryland treatment could be accounted for by the smaller leaf area. Transpiration data should therefore be expressed on a leaf area basis before any further comparison between treatments is made.

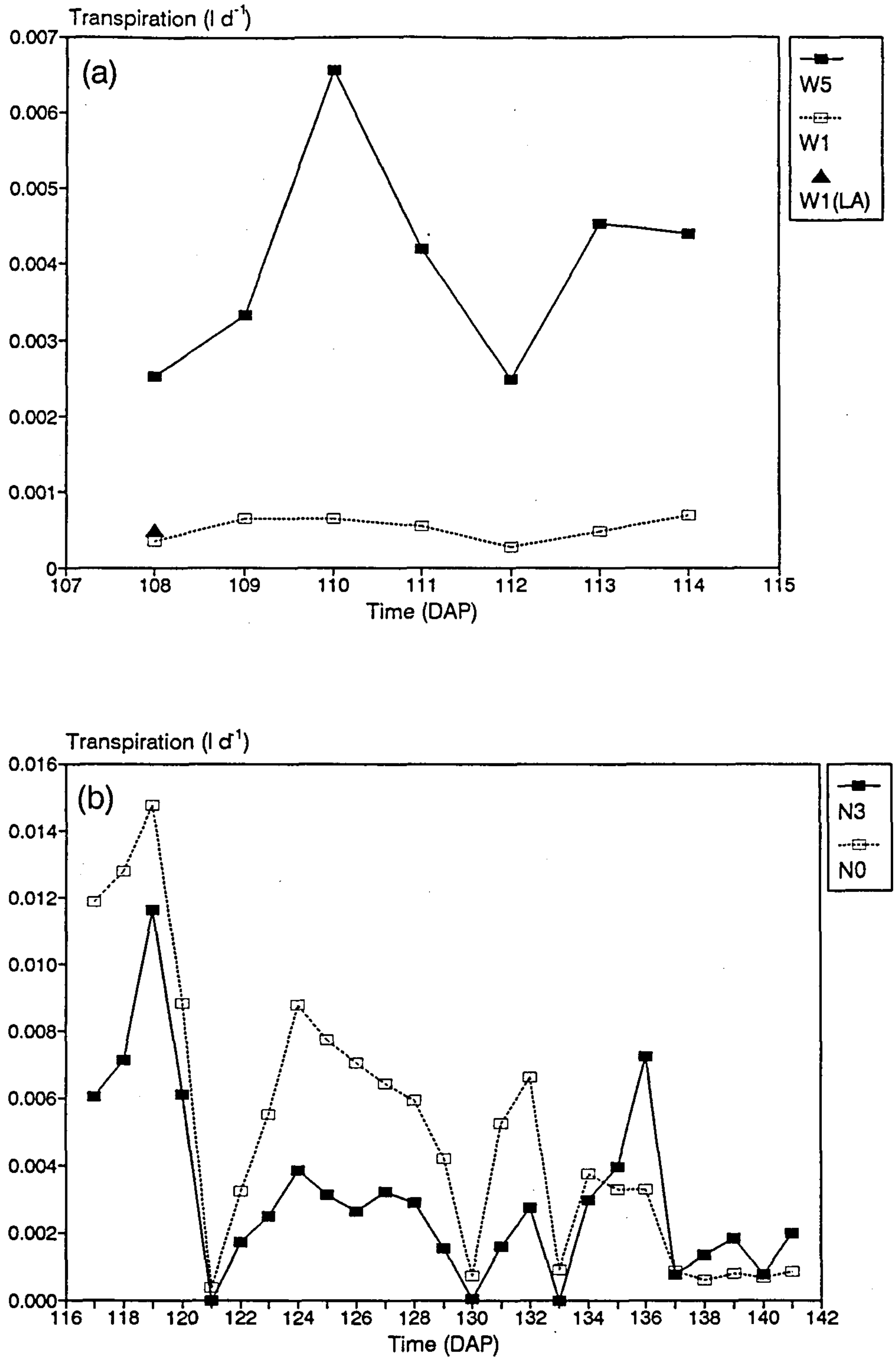


Fig. 6.1 Transpiration rates recorded during the water and nitrogen treatment comparisons made during the 1992 wheat experiment. (a) Well-watered (W5) v. dryland (W1) (both optimum nitrogen, N3), with a calculated W1 value (W1(LA)) based on comparative leaf area. Data points are means from 5 plants. (b) Optimum (N3) v. zero (N0) applied N (both W5). Data points are means from 3 plants.

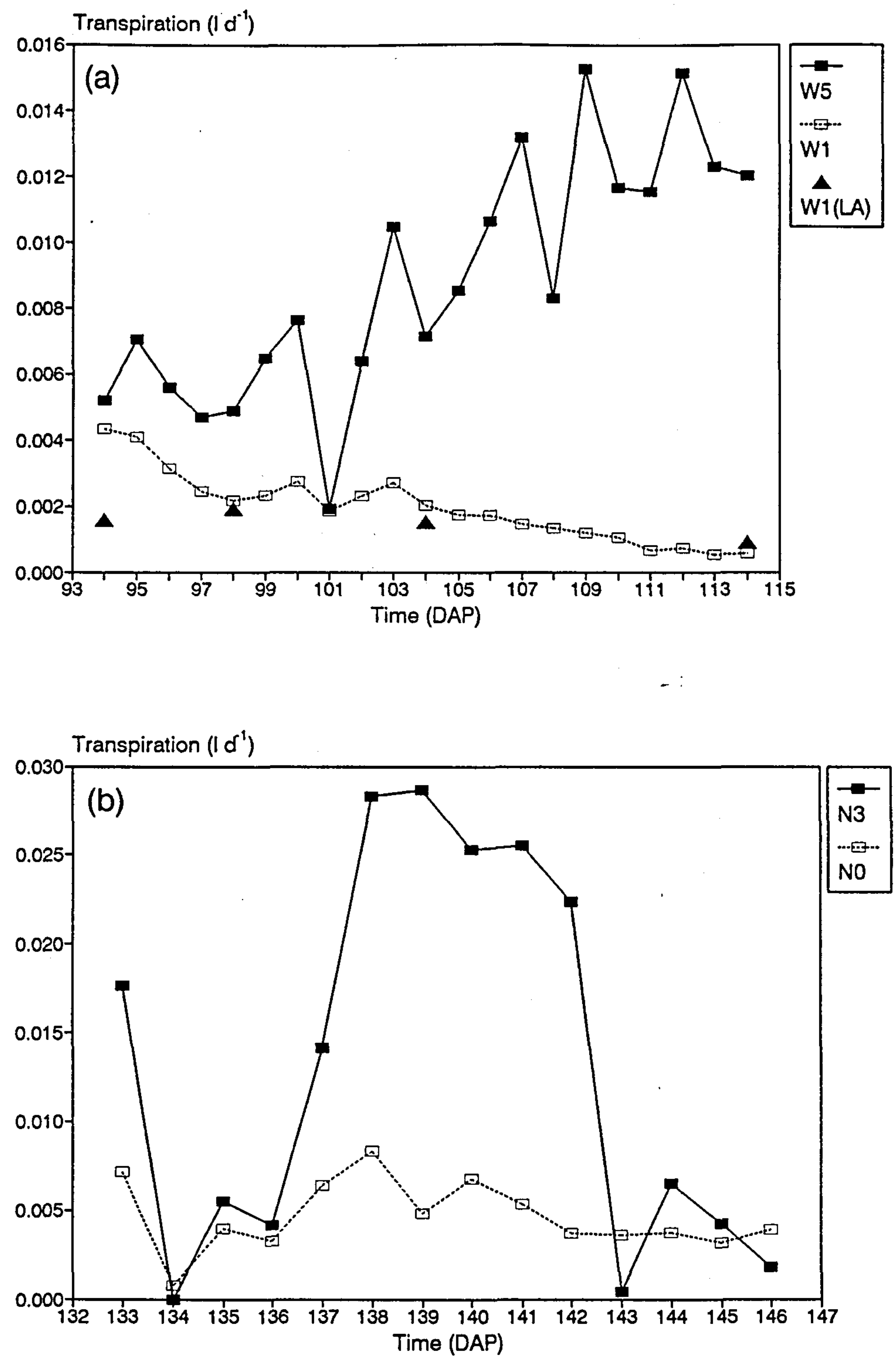


Fig. 6.2 Transpiration rates recorded during the water and nitrogen treatment comparisons made during the 1993 wheat experiment. (a) Well-watered (W5) v. dryland (W1) (both optimum nitrogen, N3), with calculated W1 values (W1(LA)) based on comparative leaf area. Data points are means from 5 plants. (b) Optimum (N3) v. zero (NO) applied N (both W5). Data points are means from 4 plants.

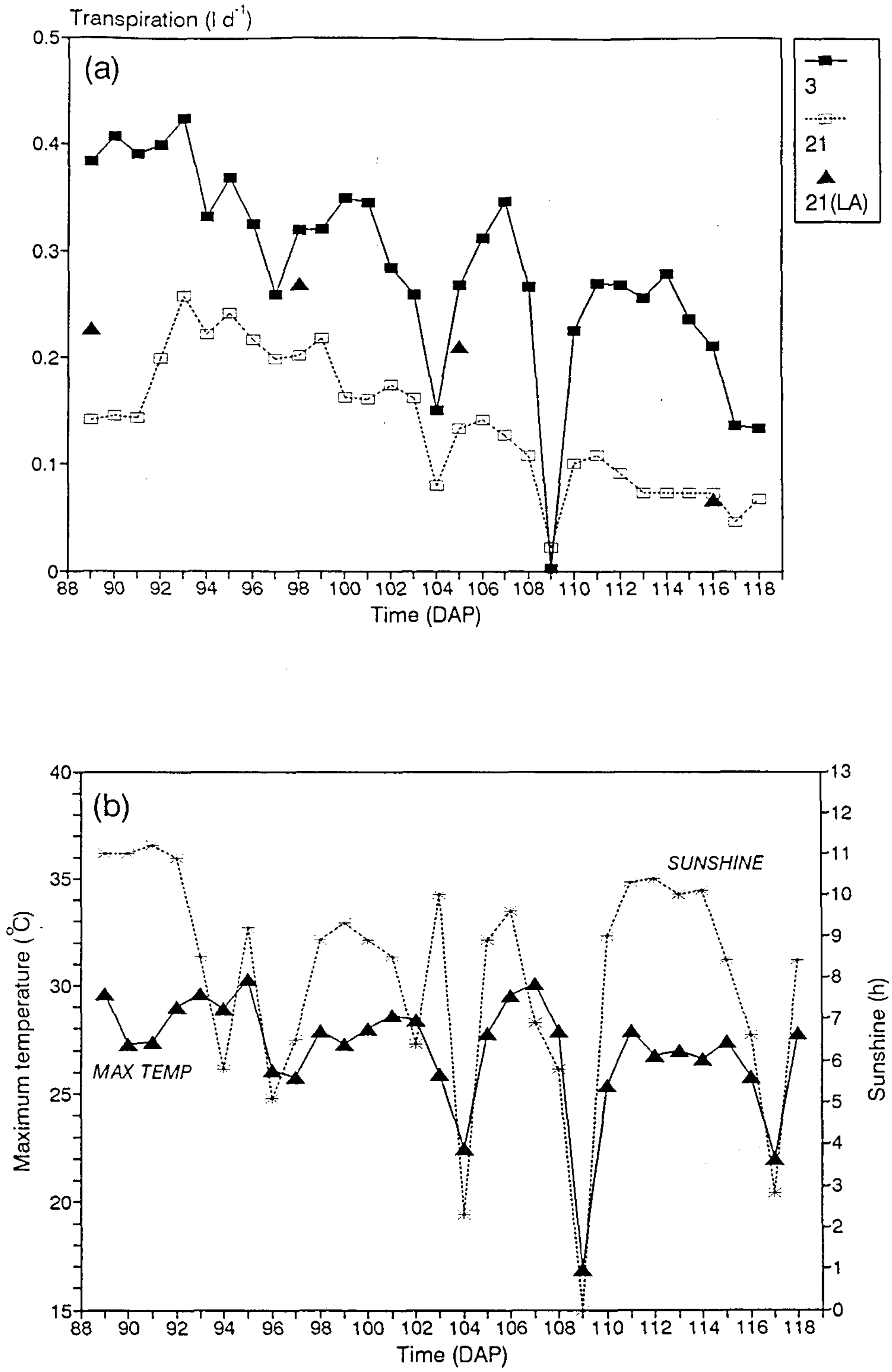


Fig. 6.3 Transpiration and meteorological data recorded during the irrigation frequency treatment comparison in the 1992-93 soybean experiment. (a) 3 d v. 21 d (under rain shelter) irrigation frequencies (cv. Hutton), with calculated 21 d values (21(LA)) based on comparative leaf area. Data points are means from 5 plants. (b) Daily maximum air temperature and number of sunshine hours.

6.1.2.1.2 Soybean

Transpiration rates (l d^{-1}) from the irrigation frequency treatment comparison of 1992-93 are presented in Fig. 6.3(a). There was a significant overall difference in transpiration rate between the 3 and 21 d (under rain shelter) treatments (GENSTAT ANOVA: $p = 0.021$). The correlation between transpiration rate and meteorological factors is very clearly seen when Fig. 6.3(a) is compared with Fig. 6.3(b), with the best correlation being with daily maximum air temperature. The influence of leaf area on the difference in transpiration rate between the two treatments was again determined (Fig. 6.3(a)), but, unlike with wheat, indicated that not all of the decrease in transpiration in the drier treatment could be accounted for by a smaller leaf area per plant. Other factors, such as a decrease in stomatal conductivity, also have an influence.

6.1.2.2 Comparison with calculated evapotranspiration

Evapotranspiration is the process by which water evaporates from a vegetated land surface as a response to atmospheric demand (de Jager & van Zyl, 1989) and comprises the sum of soil evaporation and crop canopy transpiration. A reference total evapotranspiration rate, E_o, the upper limit of atmospheric evaporative demand from natural surfaces, can be measured using a lysimeter or calculated from meteorological data. The equation derived by Penman (1948) was modified by Monteith (1965) to give the so-called Penman-Monteith equation, which includes aerodynamic and surface resistance terms. Priestley & Taylor (1972) proposed a simplified version of this equation for use when surface areas generally are wet (the atmosphere saturated), and the aerodynamic term was therefore deleted. Since the heat pulse method allows the crop transpiration component of evapotranspiration to be measured separately, it is of great interest to compare the recorded transpiration data with calculated E_o.

The PUTU crop growth simulation model (PUTU Systems, 1992; see Chapter 10) was used to calculate E_o (mm d^{-1}) from meteorological data by means of modified versions of both the Penman-Monteith and Priestley-Taylor equations. Both sets of values, and measured transpiration (now converted to mm d^{-1}), are plotted in Figs 6.4 and 6.5(a) for the wheat and soybean irrigation treatment comparison periods respectively. Fig. 6.4(a) shows that during the 1992 wheat comparison E_o was higher than the transpiration rate of both the well-watered and dryland plants. However, during the wheat 1993 (Fig. 6.4(b)) and soybean 1992-93 (Fig. 6.5(a)) comparisons there was no significant difference between E_o and transpiration in the wet treatment. Evaporation from the soil would be the major component of E_o in conditions where its surface is exposed to radiation under incomplete crop canopy cover. This was the case in the dry plots of both the wheat and soybean experiments. In the wet plots though, the crop canopy completely covered the soil surface, and in this case transpiration would form the major part of E_o. Soybean showed a very close correlation between the transpiration rate of the 3 d irrigation frequency treatment and E_o, particularly when calculated using the Priestley-Taylor equation (Fig. 6.5(b)). The modified Priestley-Taylor equation in PUTU gave a consistently higher evaporation rate than the modified Penman-Monteith, and based on the soybean comparison, appears to more accurately predict transpiration.

6.1.3 CONCLUSION

Transpiration is an important measurement in the study of crop water use, and the value of the heat pulse technique in enabling one to separate transpiration from evapotranspiration is clear. However, while the heat pulse system is ideal for such a detailed study, it is impractical to attempt to accurately scale up data from a single plant to a crop level for incorporation into growth models.

There is wide scope for further study since the system can be used with a variety of plants and positioned anywhere in a crop and at any site. The problem of being restricted to measuring from ten plants at any one time has now been overcome by Dr. Cohen, who has modified the system to include two heat pulse transmitters. Data is logged from two sets of ten plants alternately every 15 minutes.

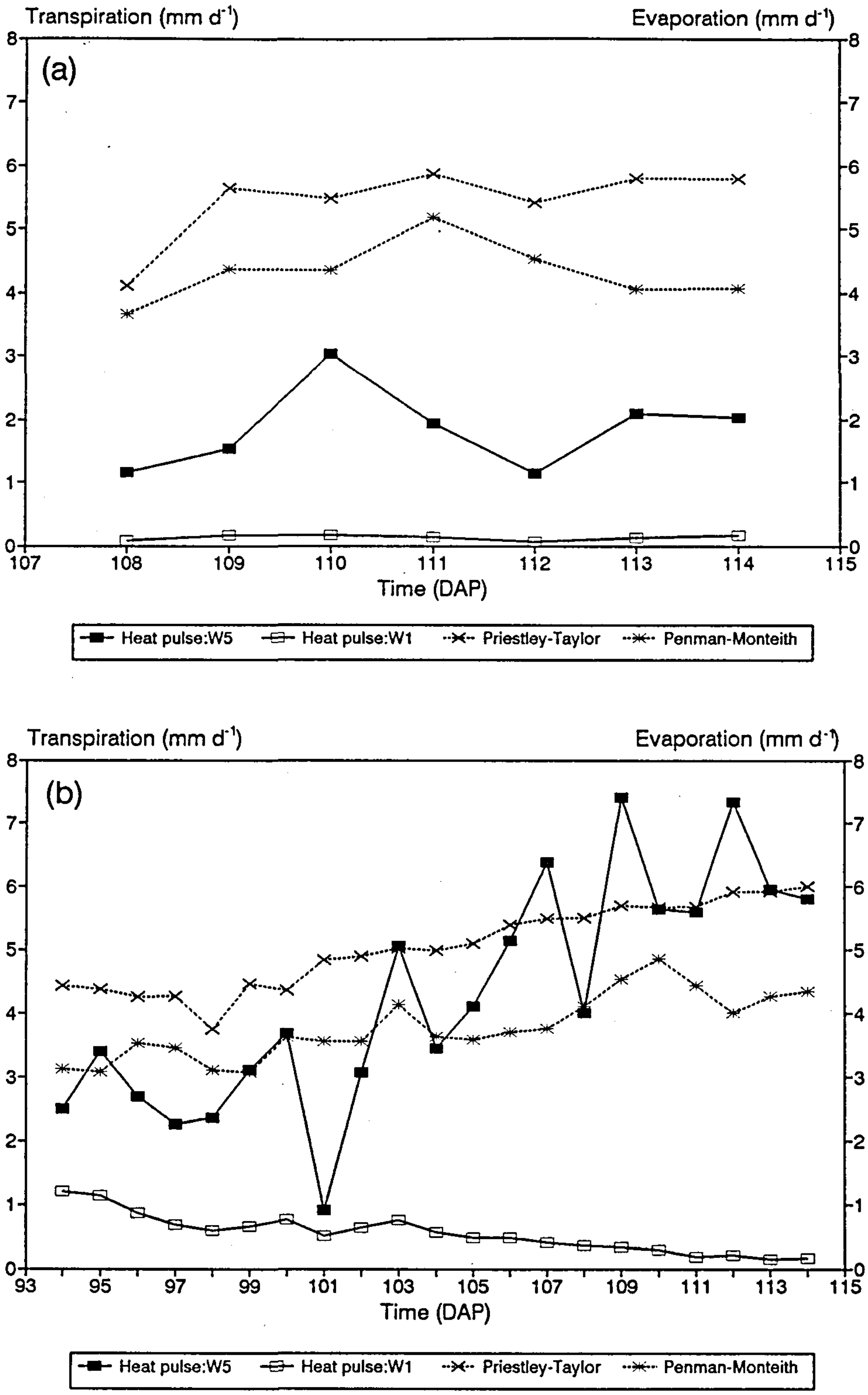


Fig. 6.4 Comparison between measured transpiration and calculated evapotranspiration, E_o, (using both the modified Penman-Monteith and Priestley-Taylor equations in PUTU) for the irrigation treatment (well-watered (W5) v. dryland (W1)) comparison periods of the (a) 1992 and (b) 1993 wheat experiments.

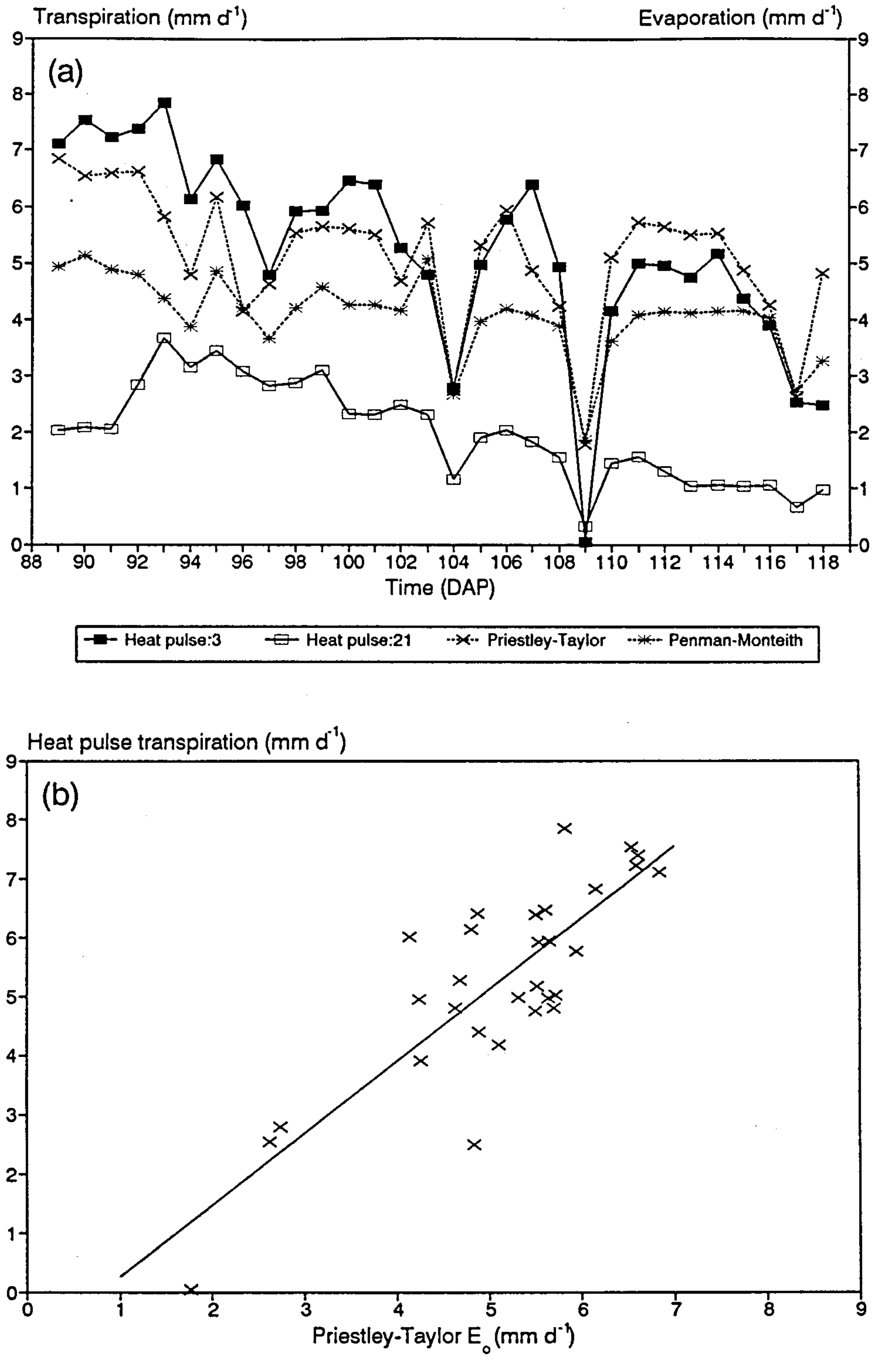


Fig. 6.5 Measured rates of transpiration and calculated evapotranspiration, E_o, (using both the modified Penman-Monteith and Priestley-Taylor equations in PUTU) for the irrigation treatment (3 d v. 21 d (under rain shelter) irrigation frequencies) comparison period of the 1992-93 soybean experiment. (a) Comparison, and (b) correlation between 3 d transpiration and Priestley-Taylor E_o. The equation of the linear regression line is: $y = 1.21x - 0.96$ ($r^2 = 0.69$).

6.2 Plant and Soil Resistances to Water Flow

Various parts of the soil-plant-atmosphere system have been subject to routine measurements in crop water relations studies, but others are more difficult to measure or even to clarify exactly what is being measured. The objective of this section of the project was to attempt to measure the water potential at various specific places in the system, namely the exposed leaves, the equilibrium value of the leaves overnight, the roots and in the soil. These measurements would then be used to calculate the resistance values for each part of the system. Unfortunately, there were certain difficulties that could not be overcome during the course of the project and so no measurement of root water potential was possible. However, few previous studies have been able to accurately measure single plant transpiration, as was possible in this study, so it was decided to continue with the attempt to calculate resistances to water flow. The heat pulse measurement of water flow rate through a single stem was used as the basis of the calculations. As the heat pulse probe was placed close to the soil surface it is assumed that the flow through the roots and the stem to the leaves was in a steady state throughout the plant.

6.2.1 MATERIALS & METHODS

Two datasets were available for the calculation of resistances: from the comparisons between the 3 and 21 day irrigation frequency treatments in the 1992-93 soybean experiment, and the W5N3 and W1N3 treatments in the 1993 wheat experiment. These studies were conducted once the crops had reached the mature stage so as to eliminate any complications arising from variations due to growth. The heat pulse measurements that formed a basis of the study could only be performed after stem elongation had been completed. Data from the routine midday and predawn leaf water potential measurements were used, with the tensiometer readings at 30, 60 and 90 cm depths that were made on selected days. An attempt was made to collect root samples in order to measure root water potential using psychrometers, but there was too much contamination by soil particles and the readings proved unreliable.

It was assumed that the water potential of the leaves was in equilibrium with the stem each morning, so that the measured predawn leaf water potential could be taken to represent the water potential of the stem at the soil surface. Water potential gradients were calculated for the various parts of the system, namely leaf to stem, leaf to soil at various depths, and stem (at soil surface) to soil at various depths. These potential gradients were then used together with plant transpiration to calculate the resistances for each part of the system.

6.2.2 RESULTS & DISCUSSION

The difficulties encountered in this study resulted in the datasets being small. An illustration of the water potential gradients recorded in the plant-soil system for both wheat and soybean is shown in Fig. 6.6. As expected the gradients in the stressed treatments were larger than those measured in the well-watered treatments for both crops. The variation in the matric potential in the soil profile was an order of magnitude smaller than that in the above-ground parts of the plant. This is due to the fact that the plant is exposed to a relatively dry atmosphere. Air at about 20 % relative humidity and an average maximum temperature of 25 °C would correspond to a potential of approximately 230 000 kPa, and provide a strong driving force for transpiration from the plant leaves.

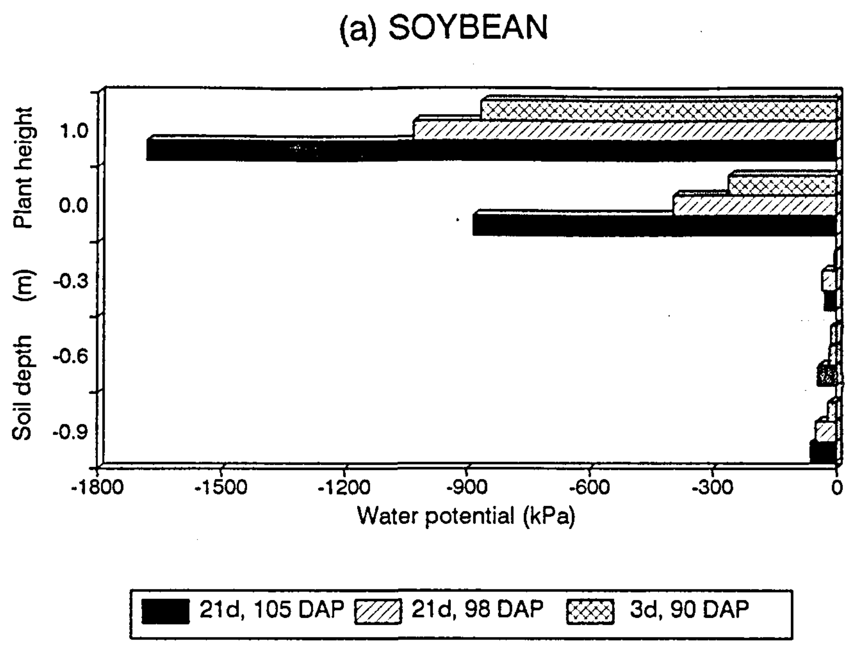
The resistances between the various parts of the system were calculated using the transpiration measured throughout the day on a single plant stem. The resistances of both the above- and below-ground sections on the well-watered plants remained low and almost constant over the 3 weeks that they were measured (Fig. 6.7). In contrast, resistances of both the above- and below-ground parts of the water stressed plants increased with an increase in stress symptoms (leaf water potential decreasing from -2090 to -3350 kPa in the wheat crop). However, the difference between the resistances also changed as the stress increased. The stem to root resistance increased more than the leaf to stem resistance as the soil dried out. It appears that the resistance to water flow between the soil and the root increased as the water stress conditions intensified. The stomatal resistance also increased sharply on the upper surface of the soybean leaves during the severe water stress conditions.

To illustrate that the below-ground resistance of soybean plants changed with water stress it is compared with both midday leaf water potential and stomatal resistance in Fig. 6.8. There is no auto-correlation between these two parameters as the below-ground resistance was calculated using the predawn leaf water potential. It can be seen that there was a range of values for the well-watered plants (-600 to -1000 kPa) and then a sharp increase in the resistance due to the water stress conditions. There was an increase in below-ground resistance as the severity of the water stress increased.

The resistance values for the wheat and soybean plants both show a reaction to the water deficit, but as the water flow per plant in the wheat tillers was generally lower than that in the soybeans (due to a smaller leaf area) the resistance values will be higher. Water flow rates measured by the heat pulse system have been expressed as mm per plant so that they can be compared, but they could have been expressed per leaf area in which case the calculated resistance values would also have been expressed in different units.

6.2.3 CONCLUSION

A start has been made during this project towards measuring all the parameters required for the calculation of resistances to water flow in the various parts of the soil-plant-atmosphere continuum. Unfortunately, at this stage it was not possible to measure all of them accurately, and further research is clearly needed to obtain a larger dataset before any comprehensive conclusions can be made.



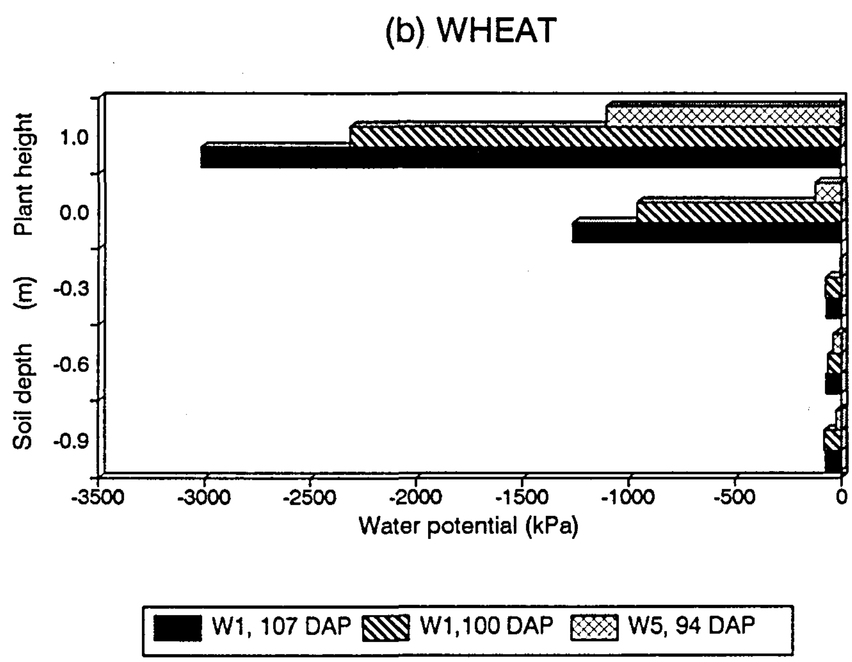


Fig. 6.6 An illustration of the water potential gradients in the plant-soil system for (a) soybean and (b) wheat, at different water treatments and days after planting.

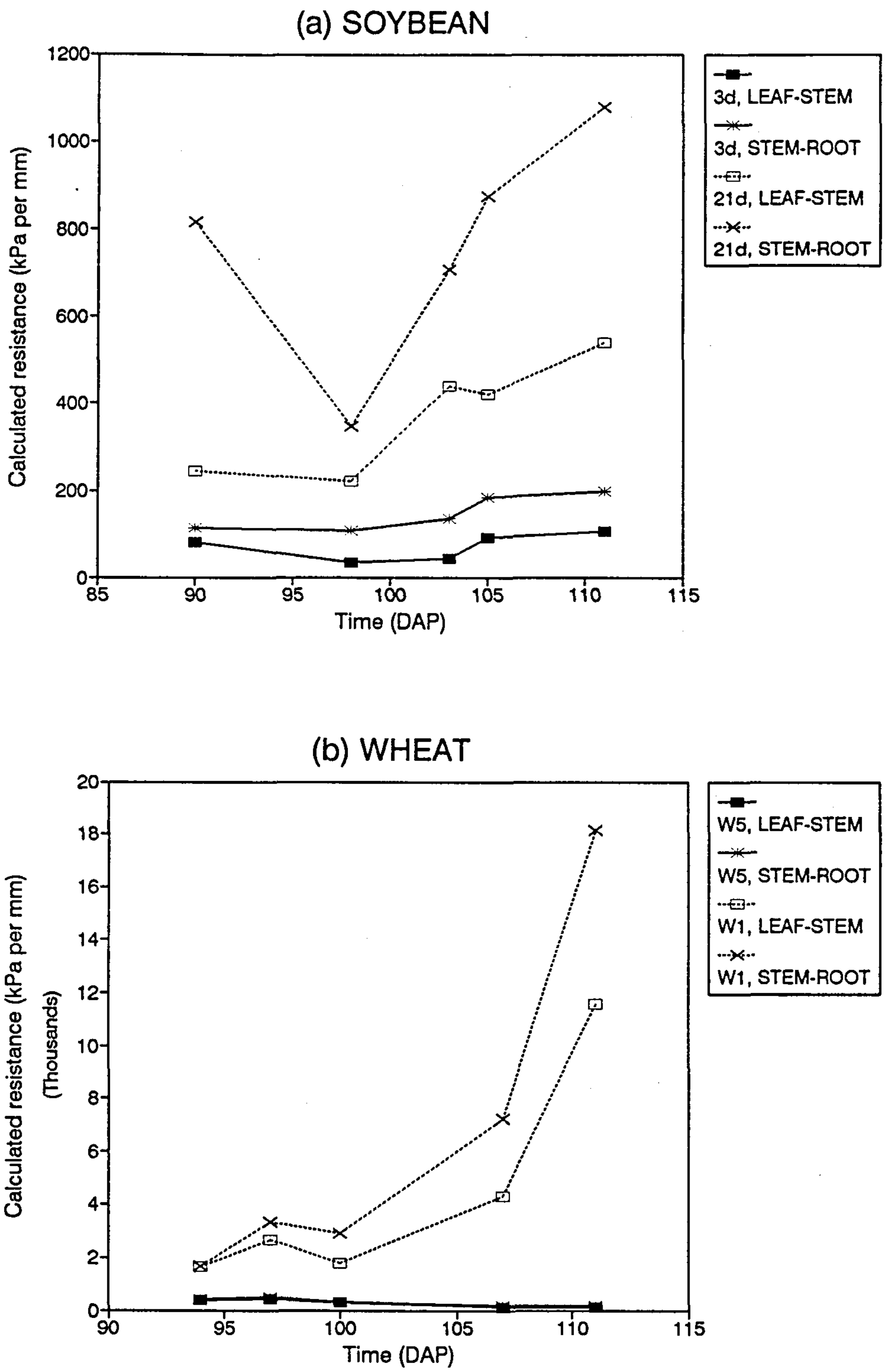


Fig. 6.7 Resistances calculated for the above- and below-ground sections of both well-watered and stressed (a) soybean and (b) wheat plants.

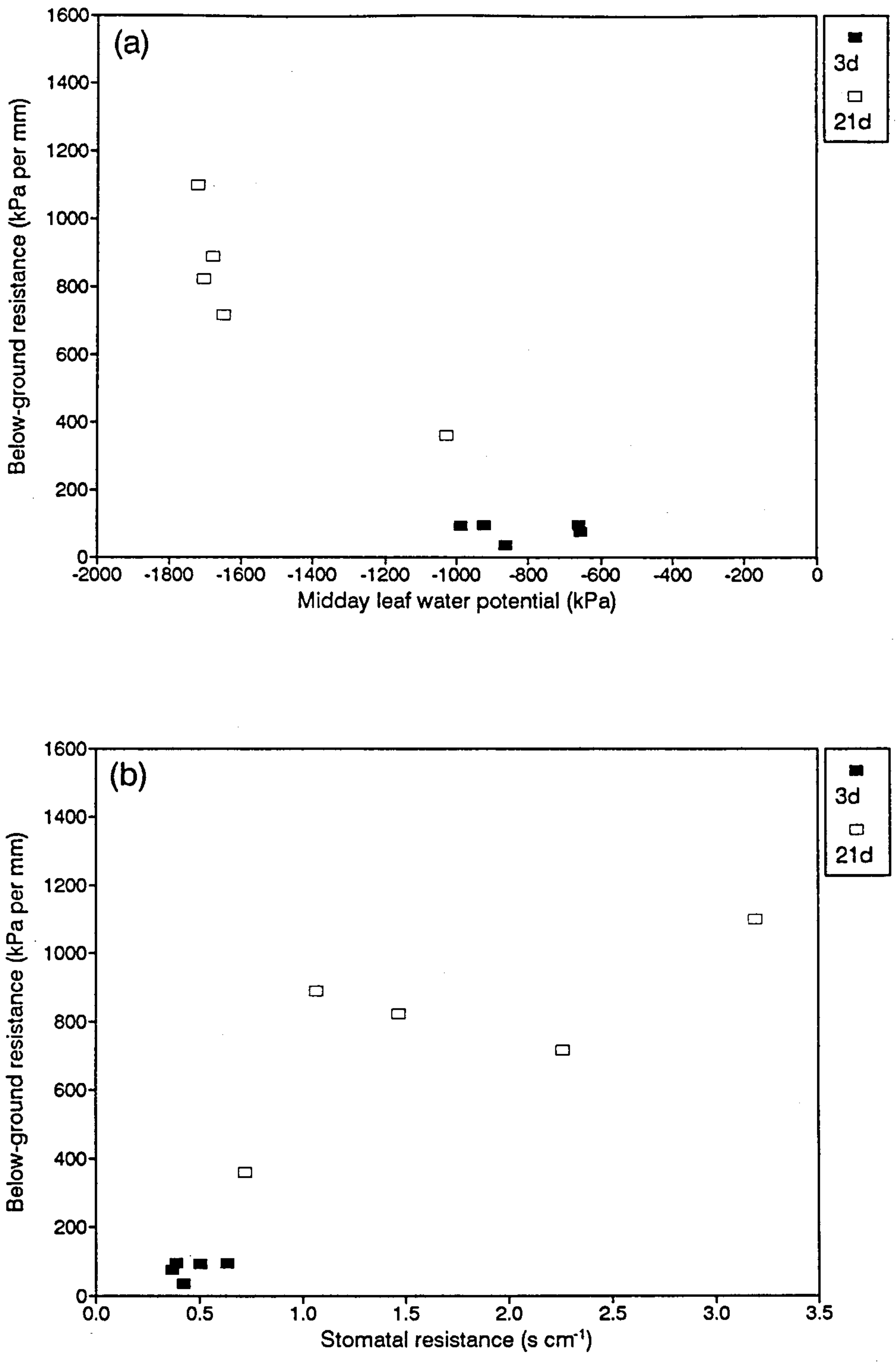


Fig. 6.8 Correlation between below-ground resistance of soybean plants and (a) midday leaf water potential and (b) stomatal resistance.

6.3 Conclusion

The study of crop water relations in this project was greatly enhanced by the use of the heat pulse technique to measure sap flow rates in single stems. The system was successfully adapted for use with delicate wheat tillers, and was calibrated for both wheat and soybean plants. It was then used to monitor transpiration rates at different water and nitrogen treatments, and its value in enabling one to distinguish the transpiration component in evapotranspiration became clear. However, the technique is a complex one, and requires a skilled operator to ensure that the large quantity of data obtained makes sense.

The objective to characterize resistances to water flow in the soil-plant-atmosphere continuum under different water-nitrogen regimes in a field experiment proved much more difficult than was originally anticipated. However, some progress was made which could form a basis for further study.

Chapter 7

CROP GROWTH AND DEVELOPMENT

7.1 Shoot Growth

As the final yield of a crop is dependent on the standing biomass accumulation, it is of utmost importance to monitor canopy development during the season. If one is to begin to explain the effects of water stress on the grain yield of wheat, it is necessary to examine the leaf area and biomass accumulation during the vegetative phase of the crop. The initial effects of water stress are first visible on leaf growth (Hsiao, 1973) which thus provides an indication of the onset of the stress. Thereafter a compounding effect of the water stress is expressed in a slower increase in leaf area and biomass, due to a feed-forward effect and the fact that the leaf is the photosynthetic factory of the plant. Therefore, if an experiment involves a water stress treatment, one must monitor both the severity of the stress and also the relative retardation in the growth of the canopy. If this is done, one will be able to compare the results from the experiment with results from similar experiments conducted at other times and places, by using the biomass accumulation as a reference point for the comparisons. These measurements are also of vital importance when crop models are tested and improved as they help to provide explanations as to why the simulated and measured yield differ. Therefore the monitoring of canopy development was one of the objectives of this project.

7.1.1 MATERIALS & METHODS

The various aspects of canopy development and growth, and the water status of both the crop and the soil, were monitored in each of the wheat and soybean experiments over the range of water and nitrogen treatments (see details in Chapter 3, section 3.5). However, since the amount of water received by the crop could only be properly controlled during the winter, only data from the wheat experiments will be discussed.

7.1.2 RESULTS & DISCUSSION

Broadly similar patterns in the development of leaf area, crop biomass and midday leaf water potential occurred in all four wheat years, and therefore data from only one season (1991) will be presented to illustrate differences between weekly irrigation frequency treatments. Data from 1990 will be shown in order to compare the weekly and two-weekly frequencies, and leaf length measurements from 1992 will also be discussed.

7.1.2.1 Leaf Length

In 1992, the lengths of the leaves on ten selected plants in one replicate of each of the treatments in the physiology plots were measured at approximately the same time each weekday from a reference level on the soil surface. The leaf measurements began with leaf 3 and continued to leaf 9 (the flag leaf). A difference in mean leaf length between the well-watered (W5) and dryland (W1) treatments (both with optimum nitrogen, N3) first became apparent for leaf 5 from about 45 DAP (Fig. 7.1(a)), i.e. almost as soon as the different water application treatments began. The difference between W5 and W1 can be seen clearly for leaf 6 and resulted in a shorter final leaf length. The severity of the water stress is shown by the fact that the final lengths of leaves 8 and 9 in the W5N3 treatment were double those of the W1N3 treatment. This difference in leaf growth was subsequently expressed in the leaf area and biomass data. The leaf length measurements were used to calculate the phyllochron intervals needed for the calibration of the CERES and SHOOTGRO crop models (see Chapter 10). The relative leaf growth rate for each leaf number was calculated from the slope of the linear part of the length v. time relationship (Fig. 7.1(b)), and the effect of the irrigation in maintaining the individual leaf growth rates can be clearly seen.

7.1.2.2 Leaf Area

Initially the leaf area index (LAI) increased in all the treatments, as the crop was planted into an almost full soil water profile (Fig. 7.2(a)). However, at optimum nitrogen conditions (N3) the leaf area in the dryland treatment (W1) fell behind that in the well-watered (W5) treatment from about 60 DAP, and the difference became particularly large at 80-90 DAP each year. Under well-watered conditions the optimum N application gave a much higher LAI than the zero N treatment in 1990, 1991 and 1993, (a difference that became noticeable from about 70 DAP each season), with W5N0 being not much higher than the W1 treatments. However, in 1992 the final LAI for W5N0 was equivalent to that for W5N3 due to a higher N content in the irrigation water that year (see Chapter 8). In all the years, under dryland conditions there was no significant difference in leaf area between the different N treatments, due to water stress being the overriding factor governing growth.

The duration of the green leaf area was affected by water stress. Under dryland conditions, senescence began earlier in the season and the leaves were dead by about 20 days earlier than in the well-watered treatments. As this coincided with the critical phase of grain-filling, the fact that the water stress was so severe as to limit the length of the season would account for the lower yields.

Fig. 7.3(a) indicates no difference between weekly and two-weekly irrigation frequencies under N0 conditions, and only minor differences during the season at a high N application level.

7.1.2.3 Biomass Accumulation

The biomass accumulation was severely affected by water deficit conditions. The dryland treatments had less than half the biomass of the well-watered treatments irrespective of the N application rate (Fig. 7.2(b)). Under well-watered conditions the effect of N application played a prominent role in the biomass accumulation, particularly during the latter half of the season when the N reserves had been depleted (except in 1992). The W5N0 treatment varied slightly between seasons but often showed an earlier senescence and decline in leaf area at a lower maximum biomass accumulation. The effects of the differences in biomass accumulation area were reflected in the final yields (see Chapter 8). As with LAI, there was no significant difference in biomass between the different N treatments under dryland conditions, and no difference between irrigation frequencies (Fig. 7.3(b)).

7.1.2.4 Leaf Water Potential

The severity of water stress experienced by the crop under the different treatments can be seen from the midday leaf water potential data (Fig. 7.2(c)). The recorded values varied in each season due to daily fluctuations in weather conditions, but in the well-watered treatments they were usually not lower than -1.5 MPa during the vegetative phase of crop development. Plants under dryland conditions tended to begin to show signs of stress from about 60 DAP, and this had become severe by 80-90 DAP when leaf water potential values were about 1 MPa lower than under well-watered conditions. Dryland potentials dropped to between -3.0 and -3.5 MPa by the end of the season. The variation in daily measurements of water potential on the stressed plots was much greater than in the well-watered ones. There was no effect of nitrogen application at either W5 or W1 in any year, showing that water supply was the overriding factor governing crop water relations. There was also no effect on leaf water potential of irrigation frequency (Fig. 7.3(c)).

7.1.3 CONCLUSION

The monitoring of the growth and biomass accumulation and plant water status on all the water and N treatments was successfully carried out throughout all the wheat seasons of the project. A good dataset is therefore available as the basis for explaining the effects of the severity of the water stress and the variation in grain yield. This dataset was also vital for the thorough calibration and validation of the models used in this project.

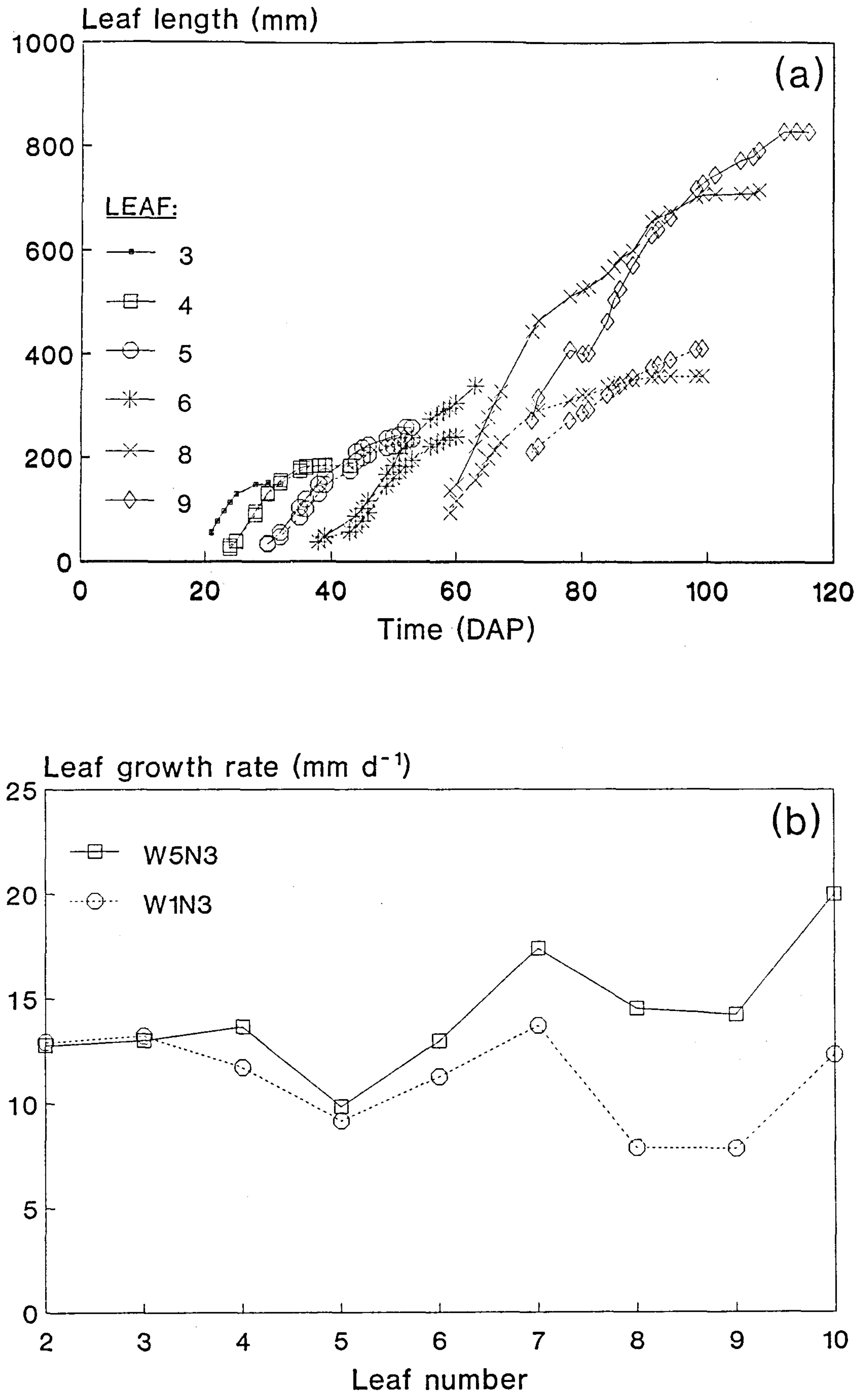


Fig. 7.1 (a) Individual leaf length and (b) leaf growth rates for the well-watered (W5 - solid lines) and dryland (W1 - dashed lines) treatments (both optimum nitrogen, N3) in the 1992 wheat experiment.

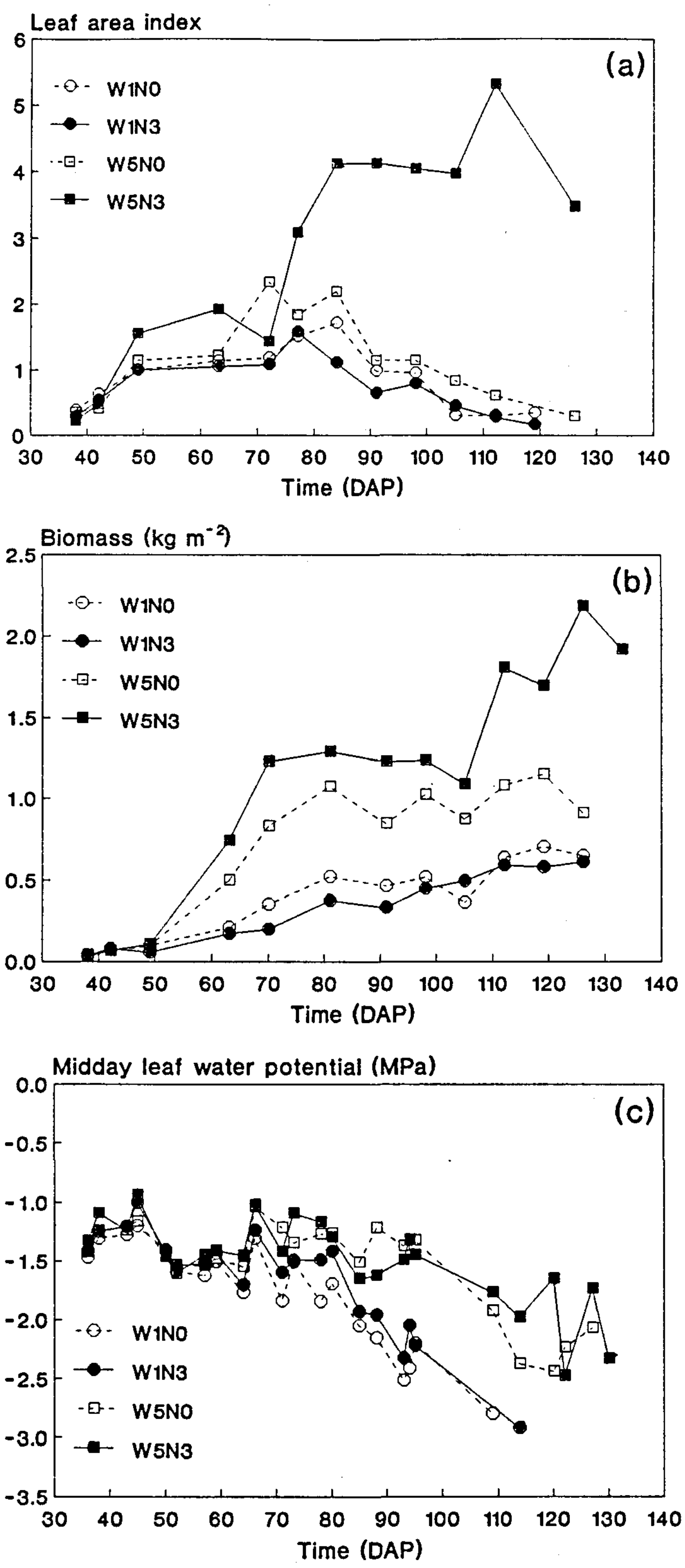


Fig. 7.2 Comparison of (a) leaf area index, (b) biomass and (c) midday leaf water potential between the well-watered (W5) and dryland (W1), and zero (N0) and optimum (N3) nitrogen treatments in the 1991 wheat experiment.

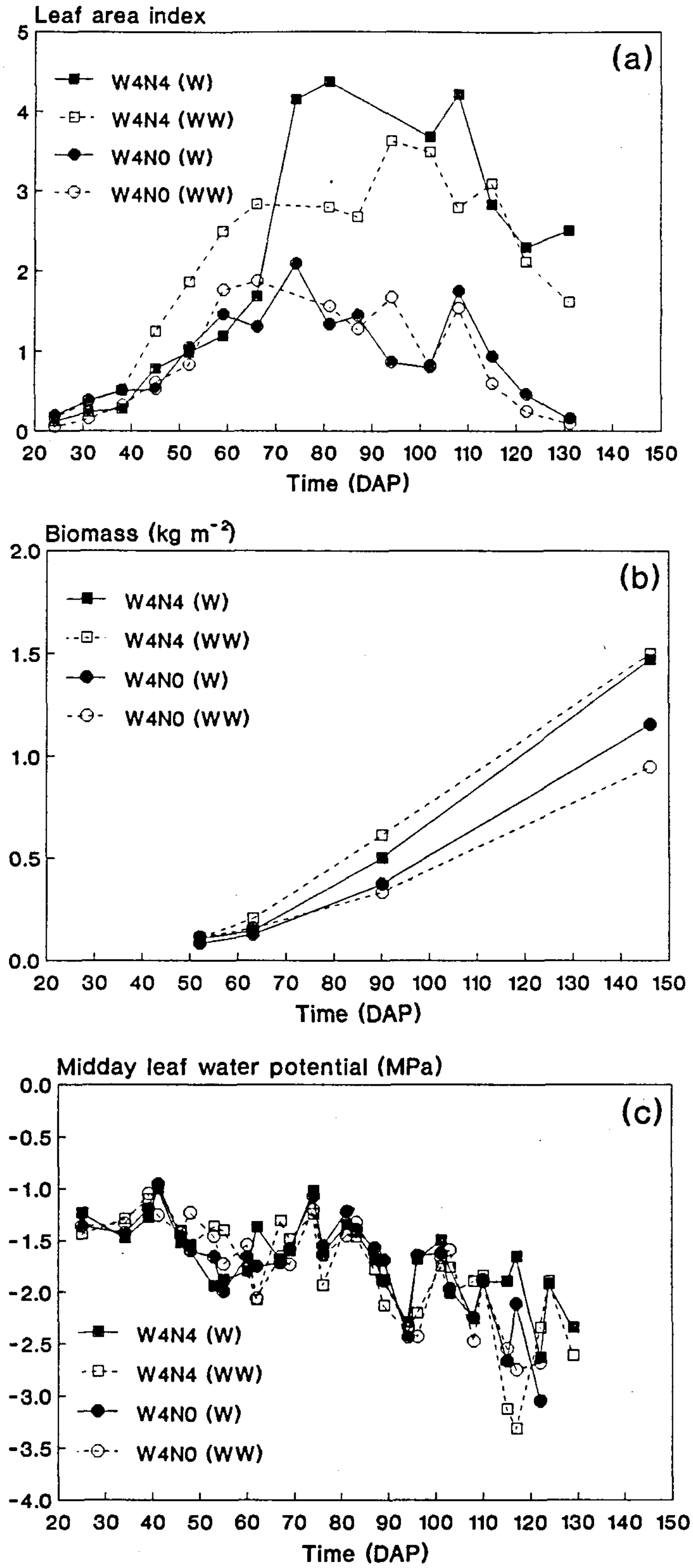


Fig. 7.3 Comparison of (a) leaf area index, (b) biomass and (c) midday leaf water potential between the weekly (W) and two-weekly (WW) irrigation frequencies for the zero (N0) and high (N4) nitrogen treatments (both well-watered) in the 1990 wheat experiment.

7.2 Root Distribution

The root growth of a crop is arguably just as important as canopy development, since it is the root system of a plant that extracts from the soil the water and nutrients which are essential for shoot growth. However, the study of roots is often neglected due their relative inaccessability. In an attempt to obtain as much data on root growth as possible, two methods were used in this project, namely the destructive soil core extraction and the non-destructive minirhizotron techniques (see description and comparison in Chapter 4, section 4.3).

7.2.1 WHEAT

Core samples were taken from the linesource plots on three occasions during both the 1990 and 1991 wheat experiments. A sample was removed from every water and nitrogen treatment combination, but from only one replicate plot in each case. Unfortunately the absence of replication renders any attempt to compare such an inherently variable measure as root growth between treatments virtually meaningless. In 1992 and 1993, root growth was monitored in the physiology plots using both the core and minirhizotron techniques, with three replicate plots in each case. As discussed in Chapter 4, section 4.3, there are advantages and disadvantages to both methods. Using minirhizotrons it was not possible to observe root growth below a depth of 1.35 m or to obtain an accurate estimate close to the soil surface. However, it was possible to follow the development of the same roots over time, thus eliminating one source of variability inherent in the destructive core method. The difficulty often encountered of being physically unable to remove cores from dry soil was also avoided. In 1992 a full dataset was obtained from the core samples, but in 1993 there were many gaps due to physical problems, and this made treatment comparisons difficult. For these reasons the results presented will concentrate mainly on the core samples of 1992 and the minirhizotron recordings of 1992 and 1993.

7.2.1.1 Irrigation treatments

The 1992 root length density profiles under well-watered (W5) and dryland (W1) conditions (both with optimum nitrogen, N3) at four core sampling times are compared in Fig. 7.4(a). These curves can be compared with those obtained by Proffitt, Berliner & Oosterhuis (1985) for spring wheat on the same soil in 1982. Both the magnitude of the RLD values in the surface layer and the maximum rooting depth are similar, but below 15 cm rooting density decreases much more sharply than previously observed. As the same pattern was found in 1991 and 1993 also, this may indicate that a plough layer is now present in the soil.

Since the curves in Fig. 7.4(a) form a definite shape, the GENSTAT Test of Parallelism for Non-linear Functions (PNLF) could be used to test for significant differences between the two treatments at each sampling time. An exponential curve is fitted of the form:

$$y = a + b*r^x \qquad [7.1]$$

where y = RLD, x = depth, a is the asymptote, b is the y intercept and r is the relative rate of increase in the slope. There was no difference between treatments at 50 DAP, as would be expected since irrigation was not withheld from the dry plots until after 43 DAP. However, at 75 DAP overall RLD in the W5 plots was higher than in the W1 plots (a and b values differ significantly; $p = <0.005$). The apparent large increase in W1 at 100 DAP was not significant, but again at 125 DAP root growth in the top 45 cm was significantly greater in the well-watered treatment ($p = <0.001$ for a and b values). This shows that the non-limiting water supply promoted an increase in below as well as above ground plant biomass. However, if the same data is plotted in terms of the % root length in each depth layer (Fig. 7.4(b)), this indicates that at 125 DAP a higher proportion of roots was present at 60-90 cm in the W1 treatment compared with W5.

Fig. 7.5(a) shows the comparison between W5 and W1 irrigation treatments in 1992 in terms of minirhizotron points of contact, with profiles restricted to the 15-135 cm depth range. Again the two treatments were almost identical at 50 DAP, but the curves thereafter showed a different pattern from the core data, which does not allow the PNLF test to be used. The best statistical analysis method in this case is the Bonferroni LSD for comparing up to 13 pairs of means (the conventional LSD_t being only valid for one pair of means). When an

LSD_B (5%) is calculated for 3 pairs of means, Fig. 7.5(a) shows significantly greater root growth in the 15-45 cm layer of the well-watered treatment at 75 and 100 DAP. However, these roots had died off by 125 DAP; the formerly clear white roots simply fading away when viewed with the camera. Since such a decrease was not observed using the core method it can be assumed that some dead roots may still have been measured. This could have been another source of variability in the attempt to correlate the two methods.

In 1993 there was insufficient core data to make meaningful treatment comparisons, but a full season of minirhizotron data was obtained. Fig. 7.5(b) shows, as in 1992, significantly greater root growth in the upper soil layer (15-30 cm in this case) of the well-watered plots from 75 DAP, with some of these roots again having died off at 125 DAP. However, at depths below 45 cm there was greater growth in the dry plots - significantly so at 120 cm from 75 DAP onwards (LSD_B (5%) calculated for 6 pairs of means). This could be attributed to the need for the plant root system to seek out available water in the drying soil.

A test was carried out in 1993 to study the effect on root growth of withholding irrigation until anthesis. One plot began as a W1N3 treatment (W1A) and the other as W3N3 (W3A) before reverting to W1 from 79 DAP. Both then became W5 treatments from 107 DAP. Minirhizotron data from the W1A and W3A plots are compared with W1 in Fig. 7.6, but in both cases there was no apparent increase in root growth after irrigation was resumed. The effect on root diameter was similarly inconclusive (data not shown). It may be that the water supply was resumed too late in order to observe any changes in root growth at 125 DAP.

Measurements of diameter made in 1992 (Fig. 7.7) show that roots in the region of 35 and 100 cm depth were initially approximately 0.5 mm wide in both the W5N3 and W1N3 treatments. However, whilst the diameter of the well-watered roots declined steadily throughout the season (due probably to ageing), that of the roots under dryland conditions decreased rapidly from 60 to 80 DAP (due presumably to a loss of turgor pressure) and then remained steady thereafter. In both treatments the final root diameter was approximately half its initial size. It would be important for roots to maintain their initial width for as long as possible as that would have a bearing on the overall surface area available for nutrient absorption. A well-watered root system is clearly optimum in this regard.

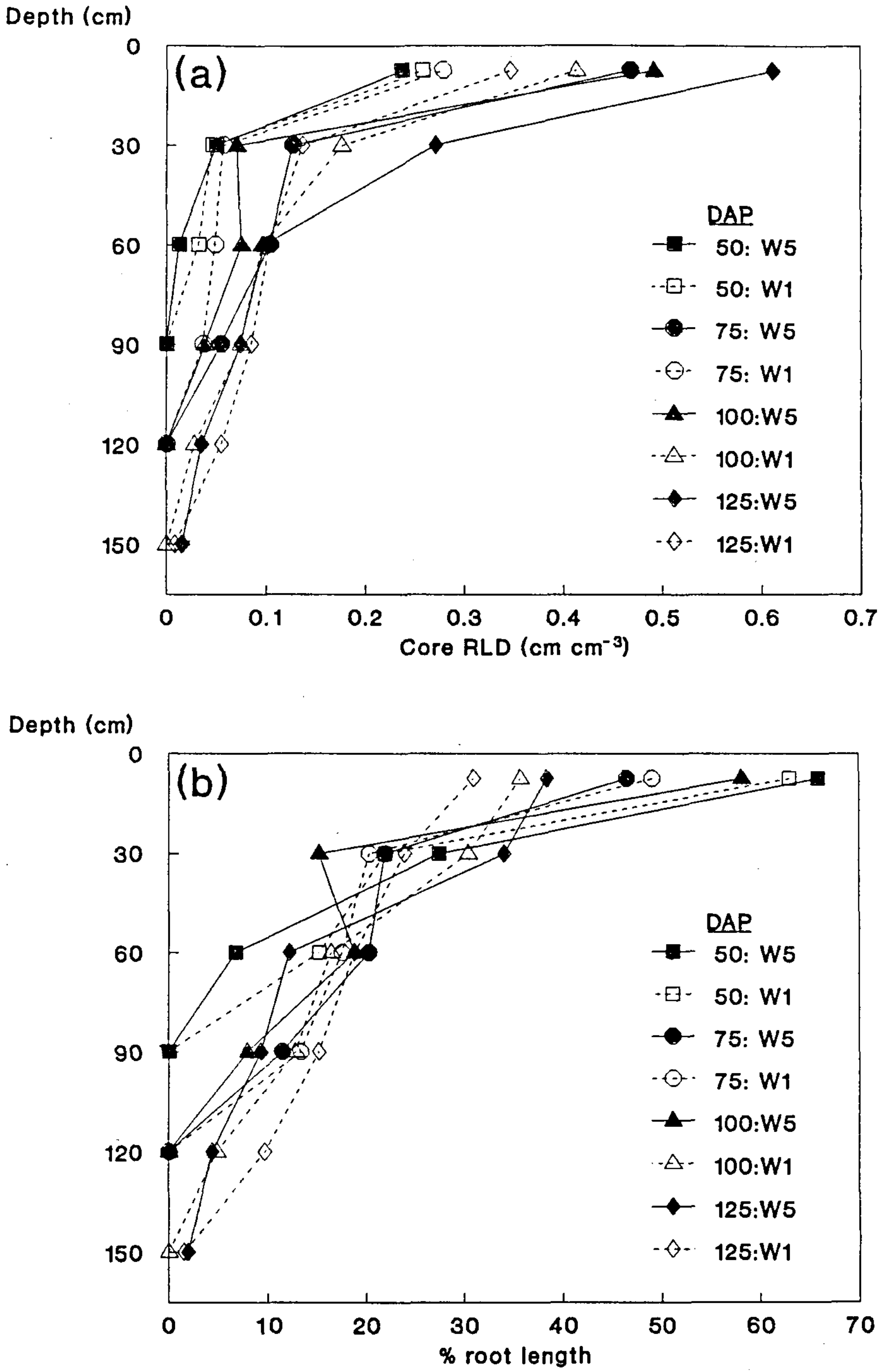


Fig. 7.4 Wheat 1992 rooting profiles under well-watered (W5) and dryland (W1) conditions (both with optimum nitrogen, N3) at four core sampling times (means from 3 plots), shown in terms of (a) root length density, and (b) % root length.

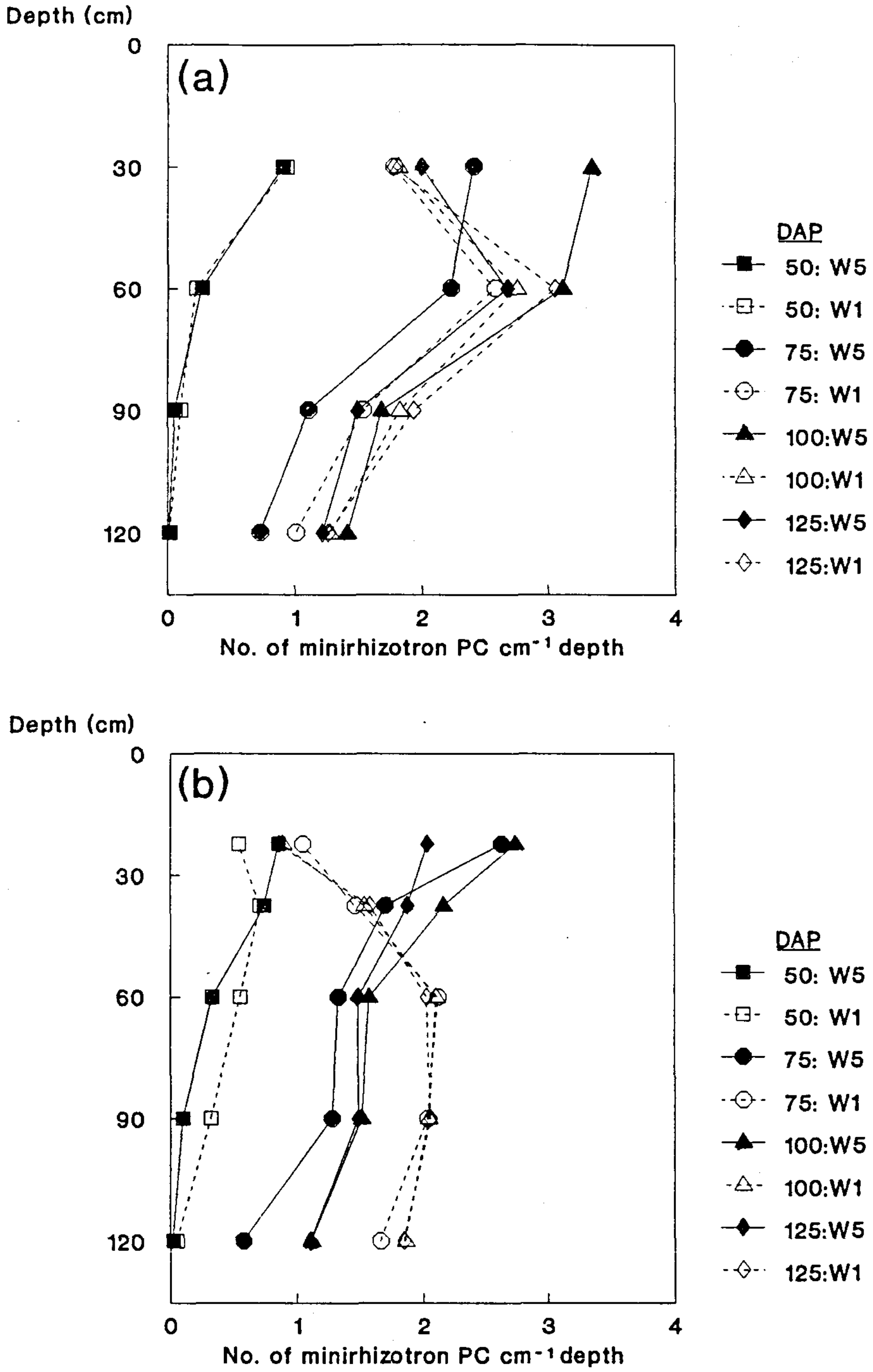
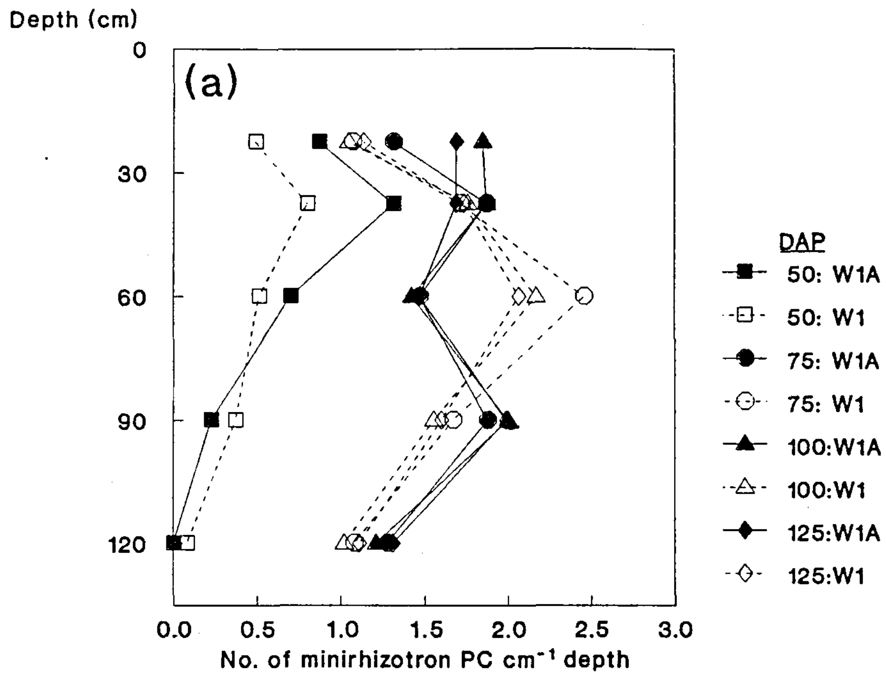


Fig. 7.5 Wheat rooting profiles under well-watered (W5) and dryland (W1) conditions (both with optimum nitrogen, N3) at four sampling times, as determined using the minirhizotron system in (a) 1992 and (b) 1993. (Data points are means from 9 tubes.) LSD_B (5%) values are: (a) 0.80 for comparing 3 pairs of means, and (b) 0.73 for 6 pairs of means.



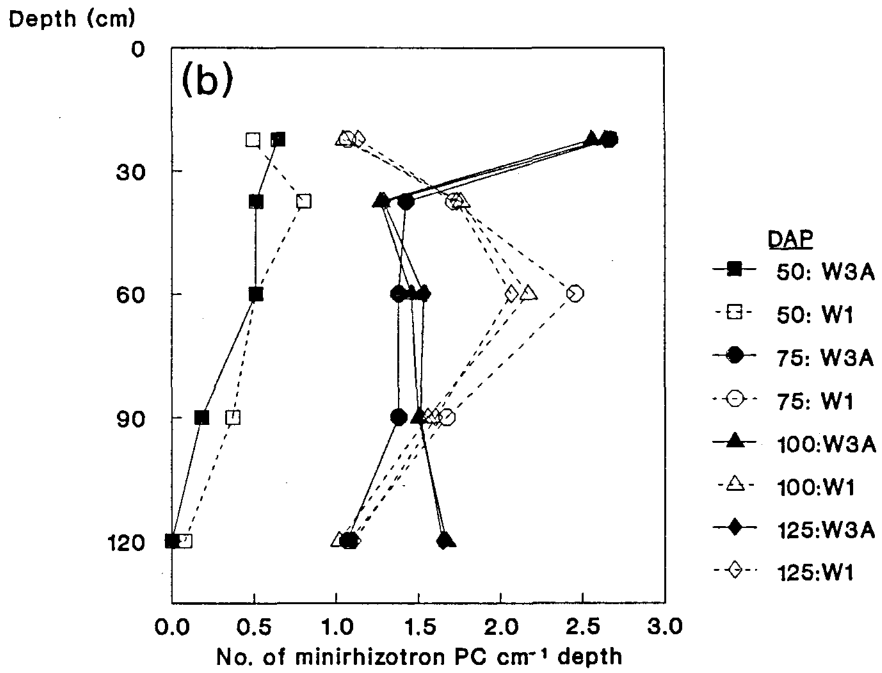


Fig. 7.6 Wheat 1993 rooting profiles for the (a) W1A and (b) W3A plots, compared with W1, as determined using the minirhizotron system (means from 3 tubes). LSD_B (5%) for 6 pairs of means = 1.05.

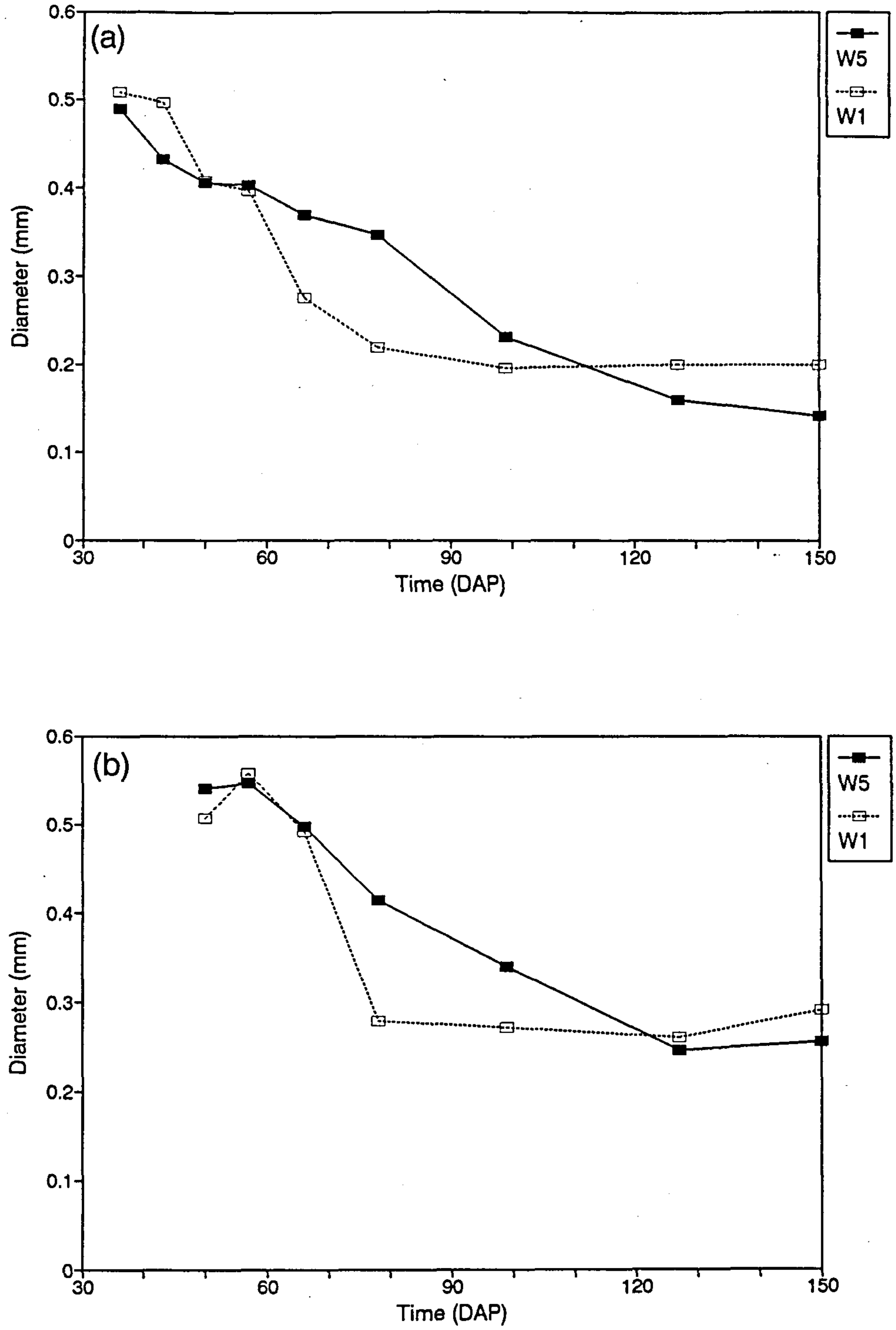


Fig. 7.7 Wheat 1992 root diameters at approximately (a) 35 and (b) 100 cm depth in both the W5N3 and W1N3 treatments (means from 3 tubes).

7.2.1.2 Nitrogen treatments

The 1992 root length density profiles under optimum (N3) and zero (N0) applied nitrogen conditions at four core sampling times are compared in Fig. 7.8, for both (a) well-watered (W5) and (b) dryland (W1) plots. No treatment differences were apparent until 125 DAP when there was a significantly higher RLD below 60 cm in the W5N0 plots (Fig. 7.8(a) - PNLF test: $p = < 0.02$ for a and b values). A similar but non-significant increase was also observed in the W1N0 plots (Fig. 7.8(b)). This result would seem to indicate that when water was non-limiting, lack of nitrogen became a limiting factor for crop growth and that this stimulated an increase in root growth deep in the soil profile in order to increase the nutrient-absorbing surface area. (However, as pointed out in Chapter 8, there was no effect of nitrogen treatment on final yield in 1992 due to the higher N content in the irrigation water.) Fig. 7.9 makes the same comparisons in terms of minirhizotron points of contact, and again shows some evidence of increased root growth at N0, particularly in the dry plots. However, the fact that only 3 replicate tubes were available for this comparison means that due to the wide variability the apparent differences between means were not significant.

The same was true in 1993 (data not presented) and shows the importance of having an adequate number of replicate tubes when attempting to compare root growth between treatments using the minirhizotron system. Eight has been quoted as the minimum requirement (see Taylor, 1987) and the 9 replicate tubes available for comparing different water treatments in this study would seem to be enough.

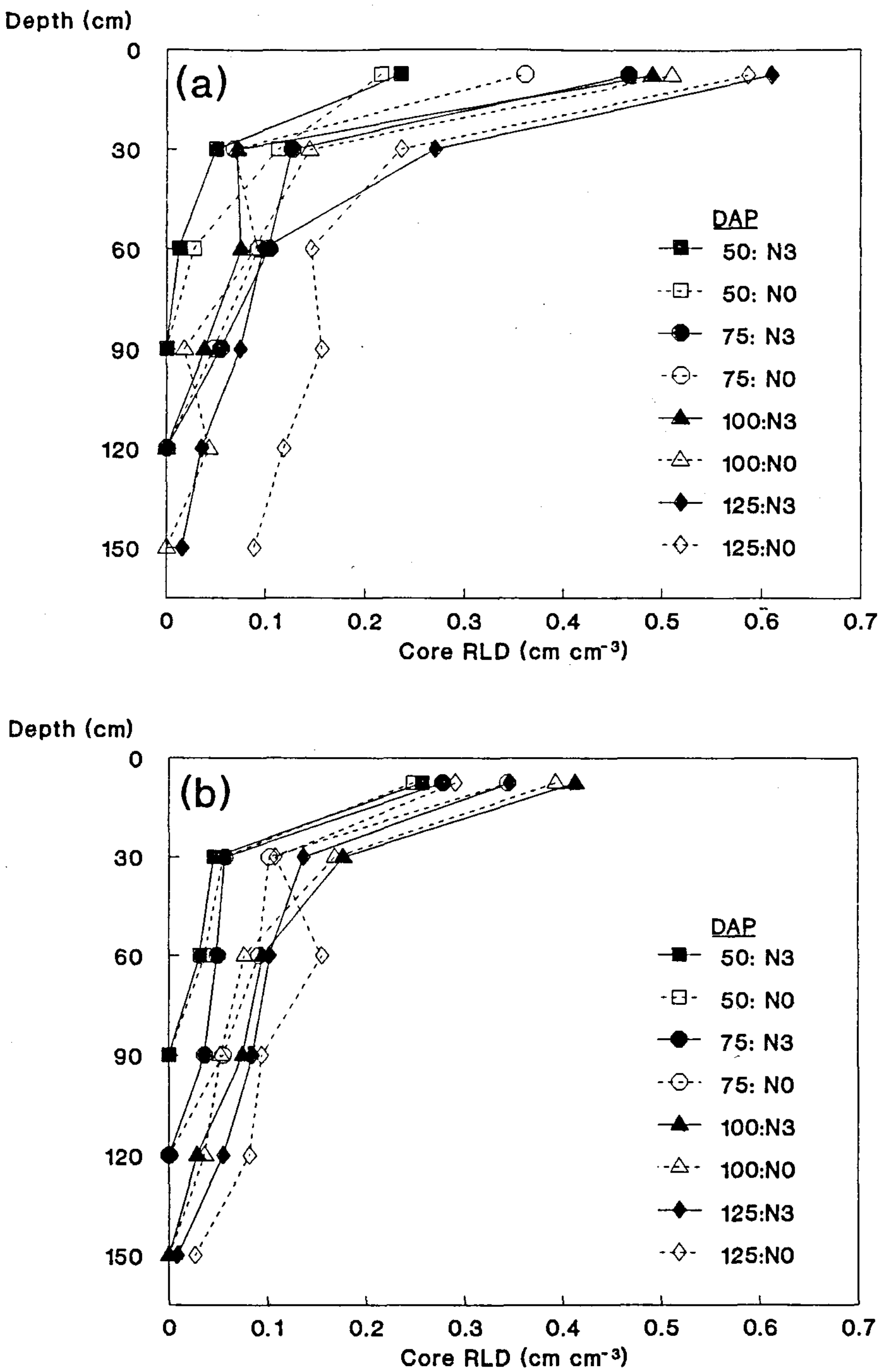


Fig. 7.8 Wheat 1992 root length density profiles under optimum (N3) and zero (N0) applied nitrogen conditions at four core sampling times in both (a) well-watered (W5) and (b) dryland (W1) plots. (Data points are means from 3 plots.)

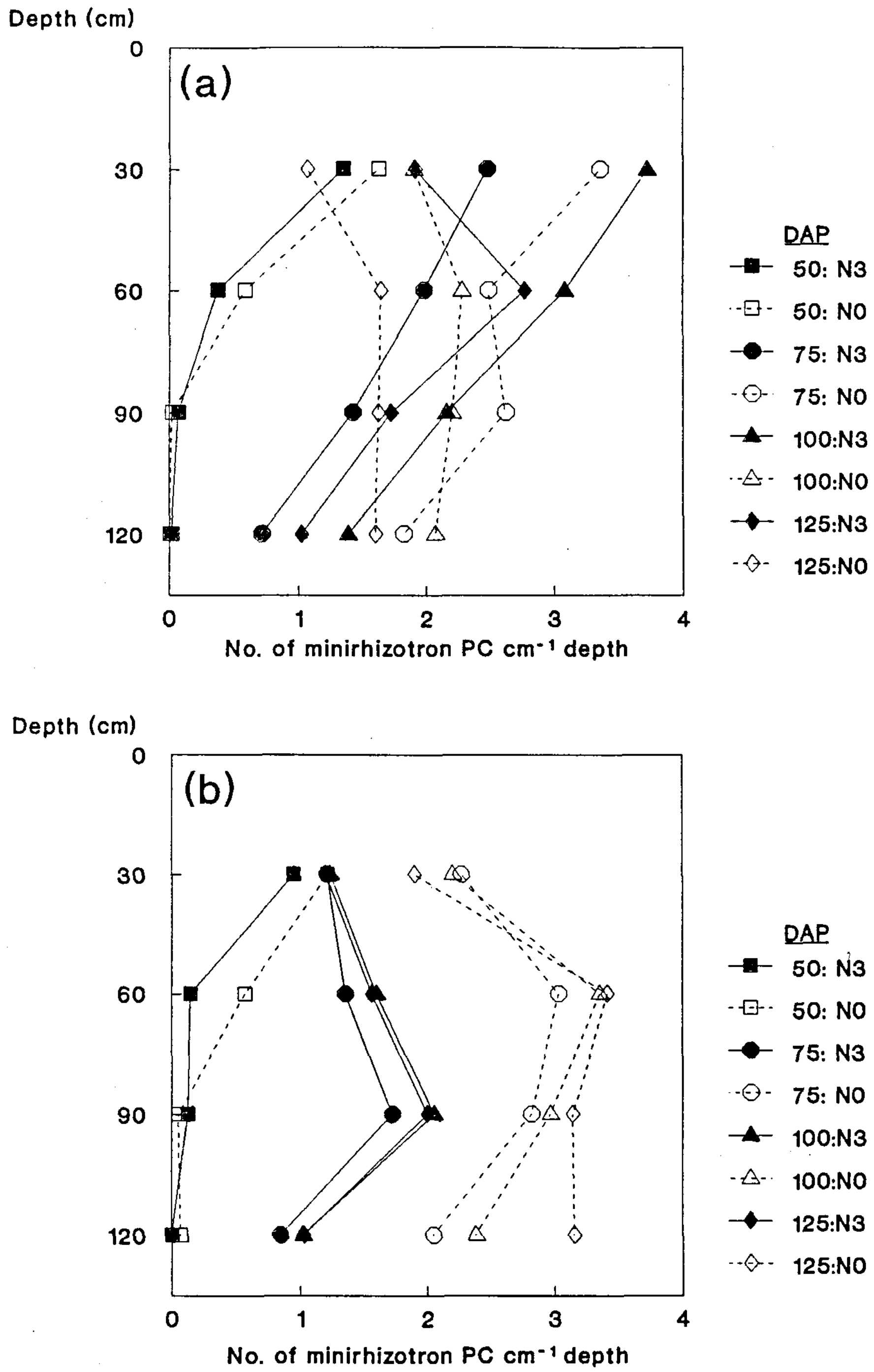


Fig. 7.9 Wheat 1992 rooting profiles under optimum (N3) and zero (NO) applied nitrogen conditions at four sampling times in both (a) well-watered (W5) and (b) dryland (W1) plots, as determined using the minirhizotron system (means from 3 tubes). LSD_B (5%) values for comparing 3 pairs of means are: (a) 1.53 and (b) 1.50.

7.2.2 SOYBEAN

No root growth measurements were made during the 1990-91 soybean experiment. In both 1991-92 and 1992-93 the minirhizotron system was used, and some core samples were taken for the purpose of correlating the two methods. In 1991-92, however, treatment comparisons between the 3 and 21 d irrigation frequencies would be misleading since both received exactly the same amount of summer rainfall and thus cannot really be considered contrasting "wet and dry" treatments. In 1993, although insufficient core data were obtained, a proper comparison could be made between irrigation treatments using the minirhizotron technique since tubes were installed in 21 d plots under the rain shelter and adjacent 3 d plots only. It was also possible to compare the two soybean cultivars, Hutton and Prima. Fig. 7.10 shows that for both cultivars, root growth was generally greater in the drier plots from 75 DAP - significantly so at 30 and 90 cm in the case of Prima (LSD_B (5%) calculated for 4 pairs of means). This would indicate that plant root development in the 21 d treatment was stimulated in order to seek out available water in the drier soil. In the 3 d plots in particular, Hutton generally showed a greater amount of root growth than Prima, and that may have an influence on the overall biomass production and final yield of these cultivars.

7.2.3 CONCLUSION

The use of both the destructive core and non-destructive minirhizotron techniques in this project allowed a fairly comprehensive study of crop root growth and development to be made. Both methods have their advantages and disadvantages, which will vary according to the soil and crop conditions at which measurements are required. The cost of the minirhizotron system will be prohibitive in many cases, but it is ideal for detailed investigations of the effects of different treatments on root morphology and turnover.

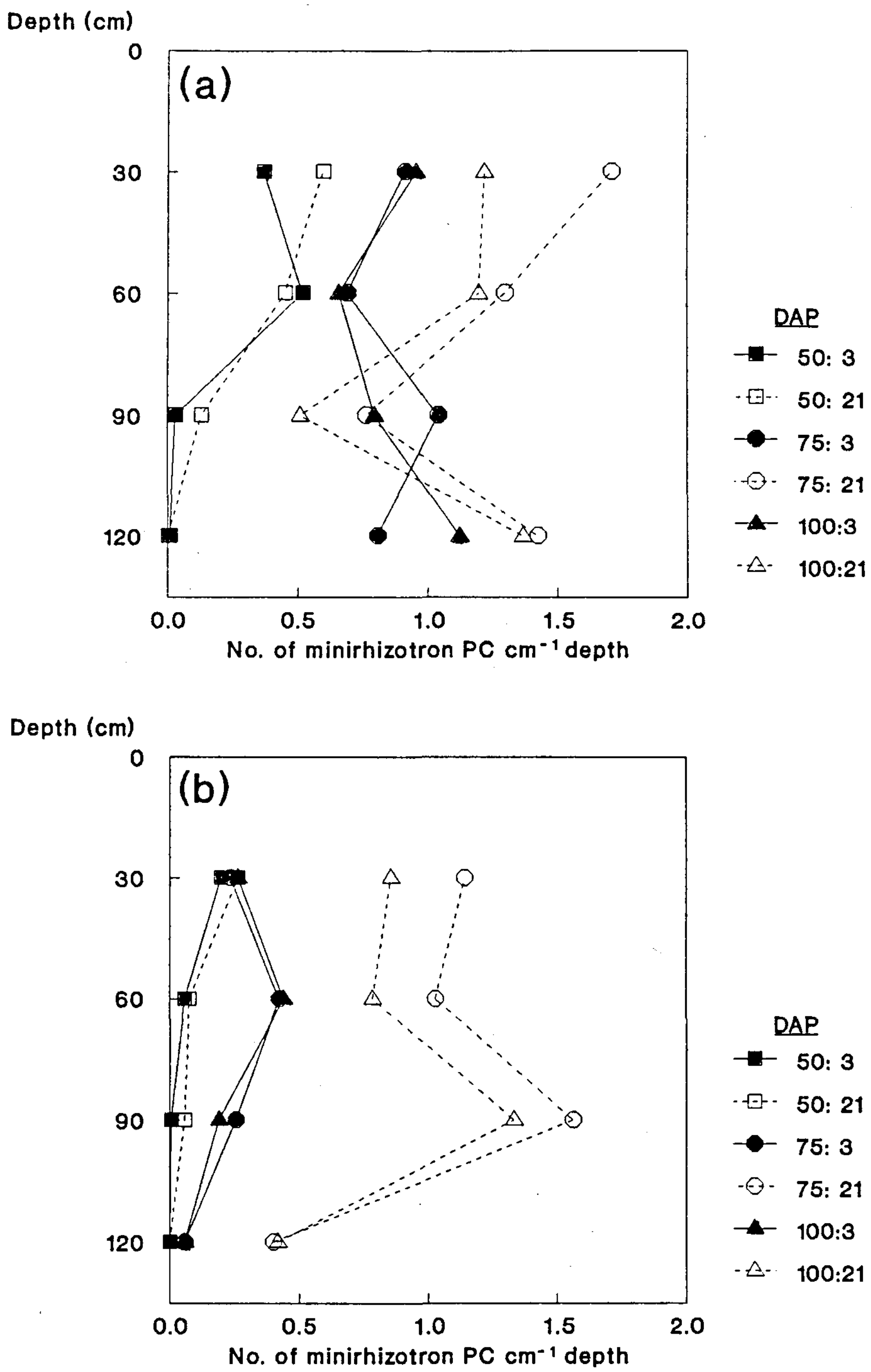


Fig. 7.10 Soybean 1992-93 rooting profiles for the 3 and 21 day (under rain shelter) irrigation frequencies at four sampling times, as determined using the minirhizotron system, for cultivars (a) Hutton and (b) Prima. LSD_B (5%) values for comparing 4 pairs of means are: (a) 0.83 and (b) 0.60.

7.3 Effect of Defoliation on Wheat Yield

Under natural growing conditions experienced during a typical season there are often events that cause the partial defoliation of the leaves of a crop. These events may be caused by insects or hail and can have devastating effects on the crop. The farmer needs to make some critical decisions following a partial defoliation, such as whether or not to continue with irrigation. This project helped to answer this question with a defoliation trial on wheat, in which the effects of defoliation under well-watered and mild and severe water stress conditions were compared.

The main effects on the crop yield of a partial defoliation are due to the changes in the sink-source relationships in the plant. Consider the effects on the source of the carbohydrates, i.e. the leaves, following such an event. The area of leaves actively involved in photosynthesis has been decreased. This drastically reduces the supply of photosynthate to the grain, which in turn decreases the final grain weight. If the defoliation is not complete then a few other questions are also posed, mainly in connection with the contribution of each leaf to the final grain weight.

For many years there has been controversy about the extent to which pre-anthesis photosynthesis contributes carbohydrates to the actual grain yield (Spietz, 1978). Many studies have been performed to investigate the contribution of assimilates from the flag leaf and stems to the grain filling. However, removal of leaves upsets the balance between the source and sink so that these types of studies are difficult to interpret, as the remaining green parts compensate for the defoliation. The percentage of carbohydrates in wheat grain contributed by pre-anthesis photosynthesis ranges from 12 % under irrigated conditions (Bidinger, Musgrave & Fischer, 1977) to 22 % under drought conditions, or up to 57 % as reported by Gallagher, Biscoe & Hunter (1976). The aim of this experiment was to investigate which leaves are major contributors to the accumulation of carbohydrates in the grain under conditions of water stress.

7.3.1 MATERIALS & METHODS

This study was carried out as part of the 1990 wheat experiment, and the defoliation was performed on 5 September when the crop was in boot stage with the flag leaves recently emerged. The defoliation treatments were as follows: (a) all leaves removed; (b) only flag leaf removed; (c) only flag leaf remaining; (d) lower leaves removed; and (e) no leaves removed, i.e. whole plant remaining (control). Five replicates (1 m length of row) were harvested (W1 at 144 DAP; W3 and W5 at 166 DAP) to calculate the final grain yield.

7.3.2 RESULTS & DISCUSSION

7.3.2.1 Plant Water Status

The degree of the severity of the water stress during the grain filling period is indicated by the midday leaf water potential values (Fig. 7.11(a)). The well-watered control plot (W5) maintained midday leaf water potential values in the range from -1.0 to -1.6 MPa except for one day (126 DAP) when -2.4 MPa was recorded due to delayed irrigation. The mild water stress treatment (W3) had leaf water potential values in a similar range. The midday leaf water potential of the severe water stress treatment (W1), however, declined to -2.7 MPa at 105 DAP and further to -3.8 MPa at 117 DAP. The midday leaf water potentials clearly illustrate the water deficit that the crop was experiencing.

7.3.2.2 Soil Water Status

The well-watered control treatment remained within the range of soil water contents where no apparent water stress should have been experienced. The mild water stress treatment was depleted to 75 % of plant available water during the season. By comparison the severe water stress treatment was depleted to 53 % plant available water at 133 DAP (Fig. 7.11(b)).

7.3.2.3 Yield

As expected the yield of the whole plant with all leaves present under the W5 control treatment was the highest at 6.12 t ha^{-1}, followed closely by the W3 treatment which produced 5.57 t ha^{-1} (Fig. 7.12(a)). The severely stressed W1 plot produced 2.08 t ha^{-1}. As expected all the defoliation treatments produced less than the whole plant treatments. Under all water regimes the treatment with all the leaves removed gave the lowest yields. Analysis of variance showed that the yields of the irrigation and defoliation treatments were both significantly different at the 1 % level. The relationships between yields of the other defoliation treatments depended on the interaction with the water stress treatments, although the interaction was not significantly different. The irrigation treatments account for 73 % of the variation, compared to 13 % accounted for from the defoliation treatments.

For the purposes of comparison the yield can be expressed as a percentage of that produced by the whole plant under each specific water treatment (Fig. 7.12(b)). Under well-watered and mild stress conditions, plants with the flag leaf removed produced a slightly better yield (82.3 and 67.2 % respectively) than plants where only the flag leaf remained (73.1 and 56.7 %). This indicated that the lower leaves form a vital part of the source for assimilates to be translocated to the grain. In contrast, under severe water stress conditions plants with only the flag leaf remaining produced a higher yield (71.7 %) than those with the flag leaf removed (66.3 %). Under these conditions the crop did not have sufficient reserves stored before anthesis to adequately fill the grain.

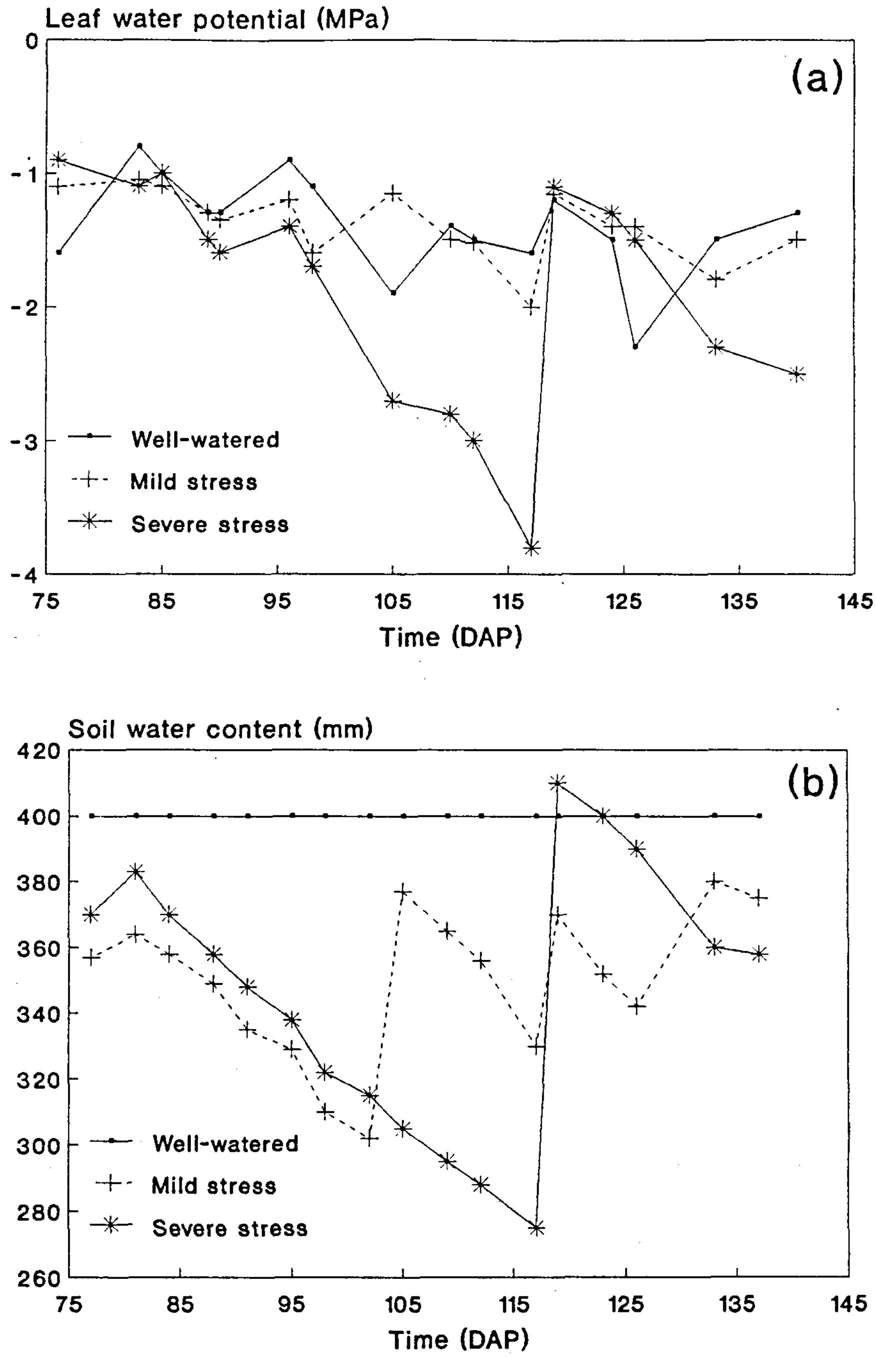


Fig. 7.11 Comparison of (a) Midday leaf water potential and (b) soil water content between well-watered, mildly and severely stressed full canopy plants.

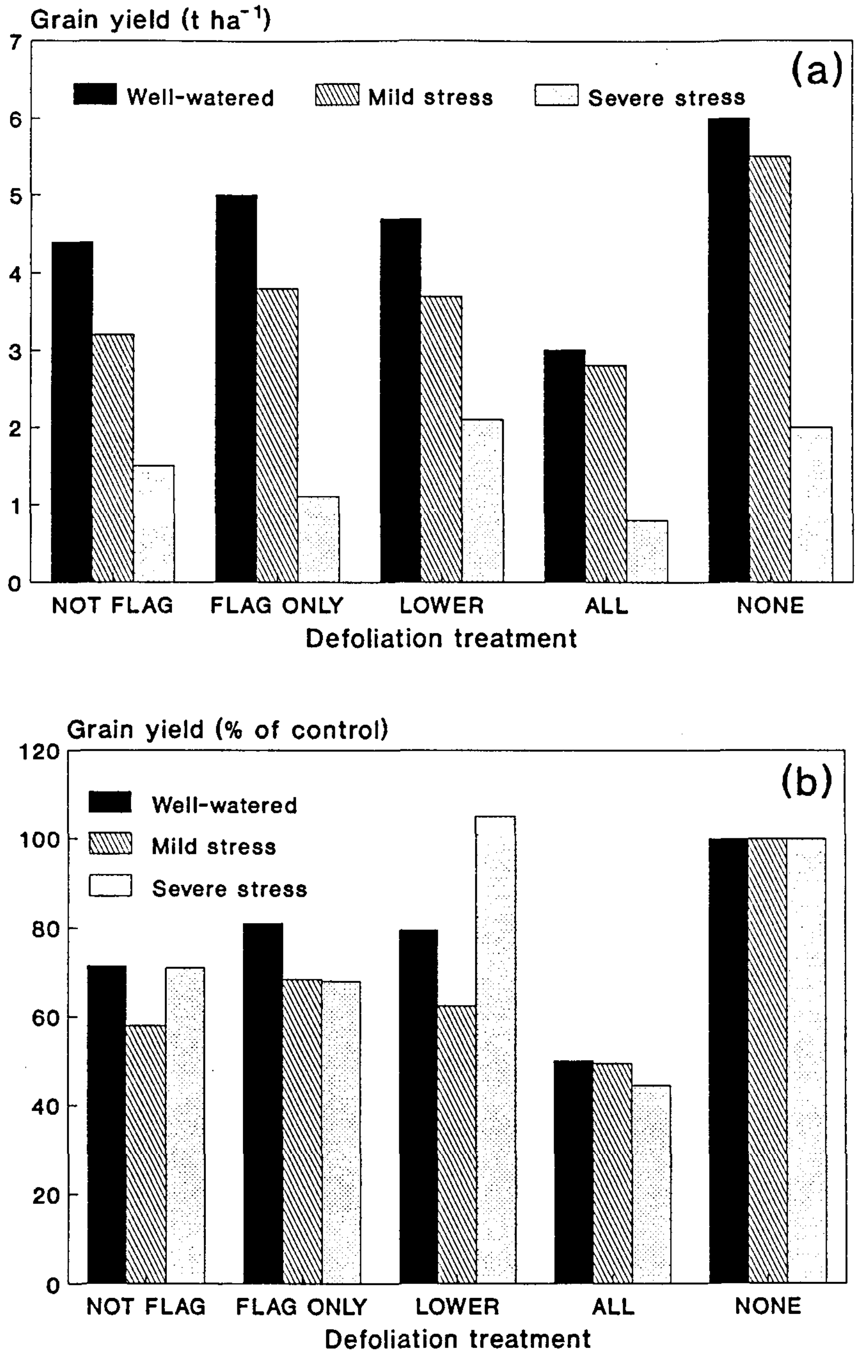


Fig. 7.12 Comparison of grain yield, expressed as (a) t ha^{-1} and (b) a percentage of the control, between well-watered, mildly and severely stressed plants at different defoliation treatments.

7.3.3 CONCLUSION

If favourable crop water status conditions are maintained following hail or insect damage, the crop should produce a reasonable yield. Preliminary results indicate that some grain quality differences are also present, but this needs further investigation. A second defoliation experiment was laid out in 1991 but, due to a problem concerning computer storage of the data, the layout of the treatments is now not known so the data cannot be analyzed. The defoliation experiments were subsequently discontinued as the LICOR photosynthetic apparatus was purchased which gave a better insight into the relative contributions of individual leaves to plant growth and development.

The practical take-home message for irrigation managers and farmers is that irrigation applications should be continued throughout the rest of the season following hail or insect damage to a wheat crop.

7.4 Conclusion

The objective to characterize the development of the crop canopy under different water-nitrogen regimes in a field experiment has been successfully achieved for spring wheat cv. SST86 at Roodeplaat. This information will be of great value both from a scientific standpoint, in that the processes involved are now better understood, and in the calibration and validation of crop growth models. In addition the growth and development of the root system was investigated in much more detail than is usually done in such studies, and some conclusions as to what a farmer should do in the event of leaf damage by e.g. hail where also reached.

Chapter 8

EFFECTS OF WATER AND NITROGEN ON WHEAT YIELD AND WATER USE

In the milieu of the modern commercial wheat farmer it is common practice to farm for optimal yields. This means that factors such as optimal but economical nitrogen fertilization, efficient irrigation scheduling, good agronomic practices and correct cultivar choice are essential for survival in the harsh economic environment. Although the cost of the actual irrigation water is not prohibitive, the expense of pumping it is rising steadily. Therefore it is vital that the farmer uses the irrigation water efficiently in order to maintain an economically viable operation and to optimize the return on input costs.

The purpose of this trial was to investigate the effect of two of the most important inputs on the growth and water use of spring wheat, namely the levels of irrigation and nitrogen application. The layout of each experiment, using a linesource sprinkler system with different nitrogen treatments, enabled an overall picture of the water-nitrogen-yield interaction to be obtained. This information was then used in the validation of the crop models, and to provide guidelines for farmers.

8.1 Irrigation and Water Use

Water is essential for plant growth, but it is also important to apply irrigation at the correct times during the life cycle of the crop. Sabale & Khot (1981), quoting Patel *et al.*, obtained higher yields when irrigation was applied at critical growth stages. Irrigation scheduling is the management action taken by the farmer in terms of when to irrigate and how much water to apply. The ideal situation would be to apply water in such a way that plant water stress is avoided entirely; however, this is not always practical or economically viable. Another important factor is that as little water as possible should move through the rooting zone and so be wasted as drainage.

As the reason for applying irrigation water is to replenish the water used by the crop and evaporated from the soil surface, it is important to study the processes involved in evapotranspiration (ET; see Chapter 6). This has led to modern irrigation models that make use of a combination of soil, plant and atmospheric parameters. One example is the BEWAB irrigation scheduling program (Bennie, Coetzee, van Antwerpen, van Rensburg & Burger, 1988) which was used in this project.

8.1.1 MATERIALS & METHODS

The BEWAB program is discussed in greater detail in Chapter 9. For the purposes of irrigation scheduling in all the wheat experiments in this trial, the following inputs were used:

a) A wheat growing season of 150 days;

b) A target yield of 8000 kg ha^{-1};

c) A soil depth of 2 m and measured % silt + clay contents for each 200 mm layer (see Chapter 3, Table 3.2);

d) A reserved rain storage capacity of 30 mm;

e) Overhead irrigation method;

f) A 7 or 14 day irrigation cycle.

The irrigation scheduling option chosen was to start with a full profile and end with a dry one (see example printout in Appendix 3). Table 8.1 gives the weekly or 2-weekly application values as determined by BEWAB, and the wheat experiments were irrigated as close to this schedule as was practically possible.

In the linesource experiments, rain gauges were positioned at each water treatment to record the actual amounts of irrigation received by the crop. Weekly neutron moisture meter readings were made in every plot, at depths of 15, 30, 60, 90, 120, 150 and 180 cm. Prior to using the neutron probe it was calibrated at each experimental site against gravimetrically-determined water contents in each soil layer, allowing the number of counts to be converted to volumetric soil water content values. A computer program in GW-BASIC was developed by Mr. Leon Peense to calculate the soil water balance for each plot using the neutron probe and rain gauge data. An advantage of this program was that it enabled crop water use in different treatments to be compared. However, a disadvantage was that it was difficult to account for drainage.

Table 8.1 Predetermined irrigation schedules according to the BEWAB program.

Days after planting	Irrigation (mm)	
	Weekly frequency	Two-weekly frequency
10	1	1
17	5	
24	8	13
31	12	
38	16	28
45	22	
52	27	49
59	33	
66	38	71
73	43	
80	45	88
87	45	
94	45	89
101	45	
108	45	89
115	45	
122	45	89
129	45	
136	41	86
143	31	
150	18	50
TOTAL:	655	653

The drained upper limit (DUL) of the soil at Roodeplaat was measured in 1990. A 1.5 x 1.5 m bare plot was thoroughly wetted by applying approximately 500 mm water. Immediately thereafter the plot was covered with a black plastic sheet to ensure that no water evaporated from the soil surface or that no rain could enter. After 21 days, the water content in each layer was measured using a neutron probe, and the total determined to a soil depth of 1.8 m.

A complete drainage curve was determined at the very end of the project on the 1991/1993 wheat experimental site. The soil profile in a similar plot to the above was wetted with sufficient water to saturate it to a depth of 3 m. Soil water content was monitored at 30 min intervals initially, so as to follow the passage of the wetting front down the profile. The plot was then covered and an intensive series of water content measurements made for a period of 21 days.

The lower limit (LL) of water in the soil was estimated in 1990 by searching the water balance files for the lowest soil water contents in each layer at the end of the season. Attempts were made in both 1992 and 1993 to more accurately determine the LL. Two of the physiology plots (labelled W5AN3; see Appendix 1) were given an optimal nitrogen application. They were maintained in a well-watered condition until anthesis (100 DAP), but then irrigation was withheld. This was designed to ensure optimal root growth and maximum water extraction from the soil profile at the end of the season. During the drying-out period the plots were protected from the rain by plastic-covered frames. However, in both years early summer thunderstorms blew the plastic off, and thus the LL could not be determined as the plots received rain.

The seasonal water use and air-dry grain yield data for each plot were statistically analyzed (using the Genstat ANOVA procedure) for treatment differences with regard to water and nitrogen application level, and (in 1990 and 1991) irrigation scheduling frequency. The water use and yield data were then used to determine the water production functions at different nitrogen levels.

8.1.2 RESULTS & DISCUSSION

In 1990 the measured DUL and the estimated LL were 458 and 295 mm respectively, to a depth of 1.8 m. Subtracting LL from DUL gives a profile available water capacity (PAWC) of 163 mm. This is the maximum amount of plant-available water that can be withdrawn from the root zone before the plants become stressed (Bennie *et al.*, 1988), leading to a decrease in crop yield. All three of these figures were subsequently used in testing the crop growth models (see Chapter 10). A similar PAWC of 166 mm was estimated from the water balance data in 1991.

If the DUL value of 458 mm is compared with the total soil water content data for each plot in each of the linesource experiments, it is evident that only in 1991 might there have been a problem with drainage occurring on several occasions. However, the 1993 drainage curve data (Fig. 8.1) indicates that the DUL on the 1991/1993 site is in fact much lower than that found on the 1990/1992 site, at approximately 400 mm. An exponential equation was fitted to the curved middle section only (Dr. M. Hensley, personal communication):

$$SWC = 439 - 18.7*\ln(t) \qquad [8.1]$$

where SWC = soil water content (mm), t = time (days) and the correlation coefficient, r^2 = 0.95. From this equation it is possible to calculate the daily drainage rate and accurately assess the volume of drainage between weekly neutron probe readings, but due to time constraints this was not done.

Fig. 8.2 gives an example, from 1992, of the change in total profile (0-180 cm) soil water content through the season for three contrasting treatments. In the well-watered (W5) treatment the profile remained full at approximately 450 mm almost throughout (i.e. close to the DUL of 458 mm). The W3 and W1 treatments both showed a steady rate of depletion, with W1 being fastest and leveling off at approximately 300 mm (i.e. close to the LL of 295 mm). Fig. 8.3 presents a similar comparison, this time showing the change in soil water content down the profile at three different times. Whereas the W5 treatment showed only a small depletion at >60 cm depth at 150 DAP, both W3 and W1 showed a much greater depletion by 100 DAP. Water contents in the top 30 cm were low in all three treatments, and the sharp contrast between this surface layer and depths >60 cm resembles the rooting profile pattern for wheat 1992 (see Chapter 7, section 7.2.1.1, Fig. 7.4(a)). If root growth, in terms of root length index (RLI = RLD * layer thickness), is plotted against water content, then two distinct groups of data points are obtained (Fig. 8.4). The highest RLI values correspond with the lowest water contents, which would be expected if soil water depletion mainly results from extraction by the crop's root system. However, at the soil surface, evaporation will be a factor too.

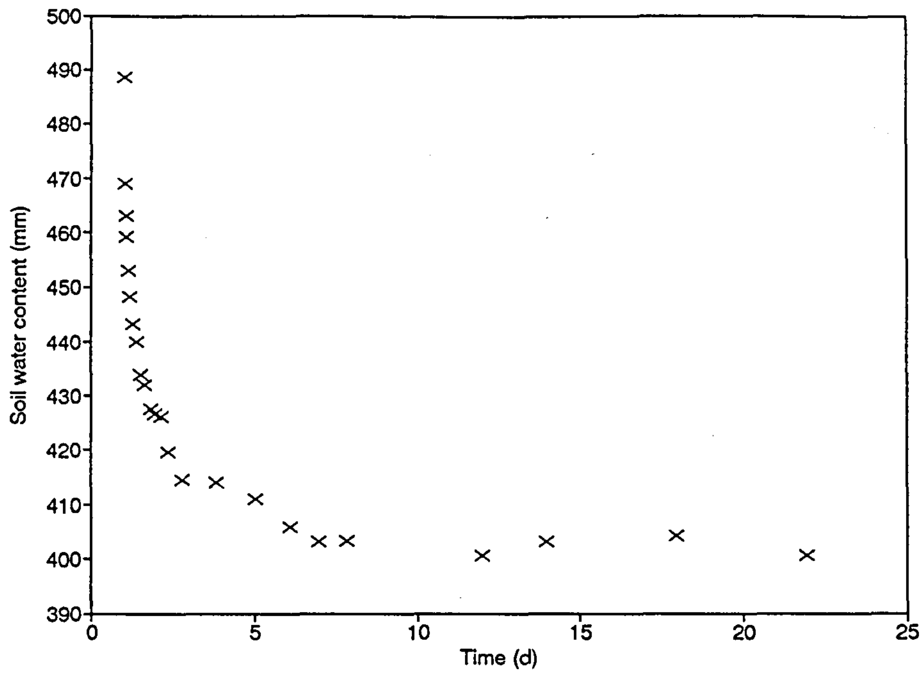


Fig. 8.1 Drainage curve determined to a depth of 1.8 m on the 1991/1993 wheat experimental site.

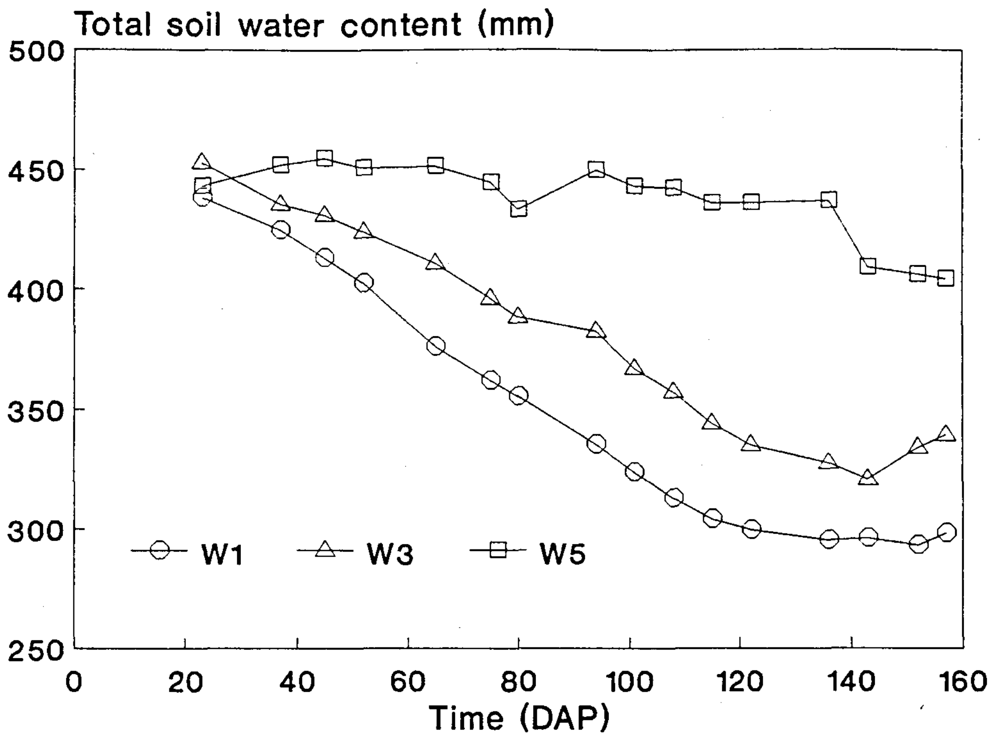


Fig. 8.2 Total profile soil water contents for three contrasting treatments (W5N3, W3N3 and W1N3) recorded weekly during the 1992 wheat experiment (means from 4 replicate plots).

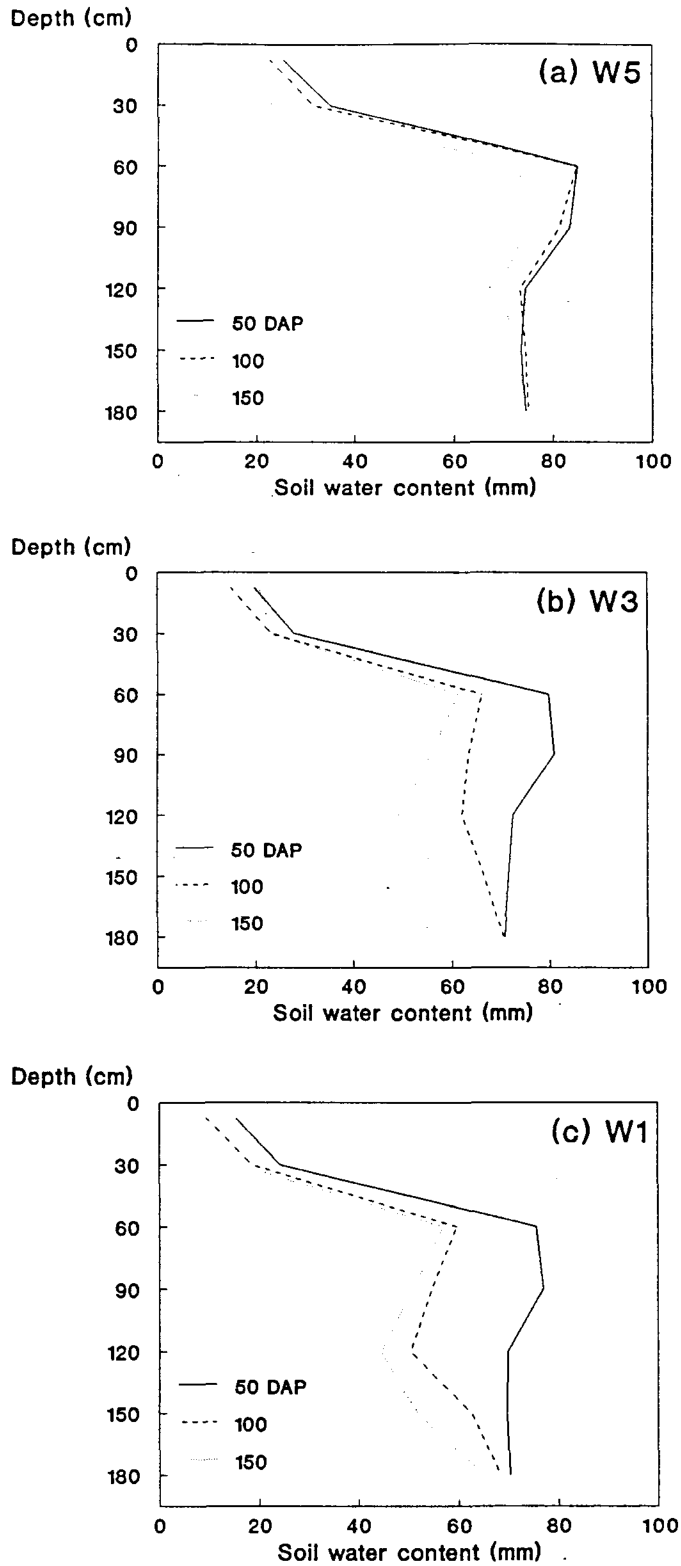


Fig. 8.3 Profile soil water contents for three contrasting treatments (W5N3, W3N3 and W1N3) recorded at three different times during the 1992 wheat experiment (means from 4 replicate plots).

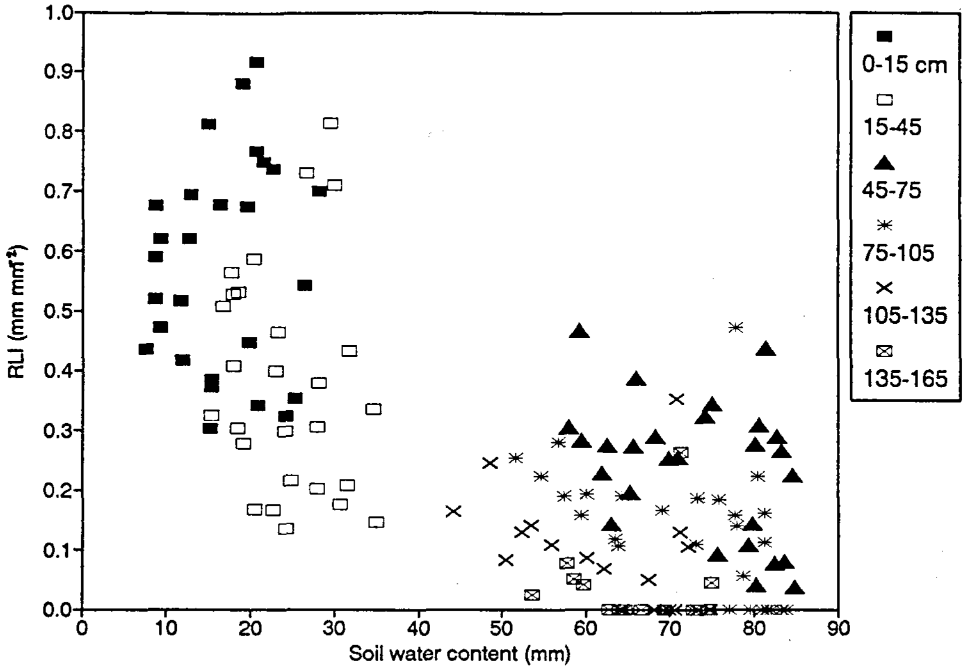


Fig. 8.4 The correlation between root length index (RLI) and soil water content in each depth layer for the 1992 wheat experiment.

Table 8.2 Results of ANOVA tests for the effects of water and nitrogen application level, and irrigation frequency (w = weekly; ww = two-weekly), on wheat grain yield and seasonal water use. [** $p < 0.01$; * $p < 0.05$; ns = non-significant.]

EXPT	YIELD				WATER USE			
	W	N	WxN	Freq	W	N	WxN	Freq
90w	**	**	*	ns	**	*	ns	*
90ww	**	**	**		**	ns	ns	
91w	**	**	**	ns	**	**	*	*
91ww	**	**	**		**	*	ns	
92	**	ns	ns	-	**	ns	ns	-
93	**	**	**	-	**	ns	ns	-

Statistical analysis of the grain yield and crop water use data (Table 8.2) showed a highly significant effect of water application level, as might be expected. The effect of the interaction between water and nitrogen on yield was also significant in all experiments except for 1992. During that year the application of nitrogen had no effect because there was already a high content of N in the irrigation water (see section 8.2). Only in the 1991 weekly irrigation frequency experiment did WxN combined have a significant effect on crop water use. Irrigation frequency had no apparent effect on yield (leading to the decision to omit the two-weekly treatment in 1992 and 1993), but did have a significant effect on water use in both 1990 and 1991.

A summary of the mean yield and water use data for all WxN treatment combinations in each linesource experiment is given in Appendix 4. In 1991, 1992 and 1993, consistent large differences in yield were observed between the two sides of the linesource in the W2 and W3 treatments, due almost certainly to the effects of wind during the irrigation periods. Such an effect was not found at the higher water levels (W4 and W5) in those experiments, nor in any water treatment in 1990. It was therefore decided that for the purposes of producing the yield-water production functions, means from all four (or three in 1990) replicate plots would be used except for W2 and W3 in 1991-93, where the two sides of the linesource would be kept separate (indicated LOW and HIGH in Appendix 4; see also diagrams of experimental layouts in Appendix 1). For each of the five nitrogen treatments, a linear regression was determined for the relationship between yield and water use in each experiment. The slopes of these lines fell into three clear groups, from which three distinct production functions were then derived (Table 8.3 and Fig. 8.5). Data points from the majority of the weekly irrigation frequency experimental treatments where nitrogen was added (N1-N4) fall into Group I. The slope of the overall regression is 10.25 kg ha^{-1} mm^{-1}, similar to the values of 11.38 determined by Bennie *et al.* (1988) and 12.33 by Streutker (1983) for spring wheat. Small discrepancies could be accounted for by different conditions of e.g. soil and climate, and the use of different cultivars. The N0 treatments (except in 1992), together with N1 in 1991 (weekly frequency), fall into Group II, with a much lower slope of 4.51 kg ha^{-1} mm^{-1}. Here a lack of nitrogen overrides the effect of increased water supply and limits the potential yield. This did not occur in 1992 due to the higher N content in the irrigation water, so the N0 production function for that year falls into Group I. Group III comprises the N2-N4 two-weekly frequency treatments, with a much higher slope of 15.78 kg ha^{-1} mm^{-1}. This indicates that with nitrogen non-limiting, optimum yields can be obtained using a lower amount of irrigation if it is applied once every two weeks instead of every week. The highest yields were also obtained at this lower frequency (Fig. 8.5). Since the crop needs about 50 mm of water per week during the period of peak demand, this means that sufficient water was available in the soil profile between the two-weekly irrigations to meet the evapotranspiration demand without subjecting the plants to stress. Over the whole season a lower fraction of water would be lost via evaporation from the soil surface when it is wetted less frequently.

For commercial wheat farmers these yield-water use relationships are very important because of the cost implications, and they can be used in seasonal decision-making. The efficiency of crop water use was clearly higher when irrigation was applied at two-weekly intervals (at optimum N) compared to a weekly application. Based on the Group I and II regression lines (Fig. 8.5), in order to achieve a target yield of 8 t ha^{-1}, 700 mm of water are required at the weekly irrigation frequency but only 525 mm if irrigation is applied every two weeks. This represents a saving of 25%.

Table 8.3 Yield-water production functions for spring wheat (cv. SST86) at Roodeplaat. [w = weekly and ww = two-weekly irrigation frequency; Y = yield (kg ha^{-1}); WU = seasonal water use (mm).]

Group	Treatments/Experiments	Overall regression
I	N0: 92	Y = 10.25WU + 798
	N1: 90ww, 90w, 91ww, 92, 93	(r^2 = 0.77)
	N2: 90w, 91w, 92, 93	
	N3: 90w, 91w, 92, 93	
	N4: 90w, 91w, 92, 93	
II	N0: 90ww, 90w, 91ww, 91w, 93	Y = 4.51WU + 1848
	N1: 91w	(r^2 = 0.36)
III	N2: 90ww, 91ww	Y = 15.78WU - 411
	N3: 90ww, 91ww	(r^2 = 0.86)
	N4: 90ww, 91ww	

8.1.3 CONCLUSION

It should be noted that the yield-water production functions determined above will strictly speaking only apply to similar conditions with regard to spring wheat cultivar, soil characteristics and climate. However, the economic advantages of irrigating once every two weeks instead of once a week are clear: it can save time, labour and money. The deciding factors for farmers would remain the available water storage capacity of their soil, as well as their irrigation cycle and the manufacturer's recommended application rate for the specific irrigation system. It is also important to keep in mind the requirements of the crop, and climate factors such as evapotranspiration rate and the occurrence of hot spells.

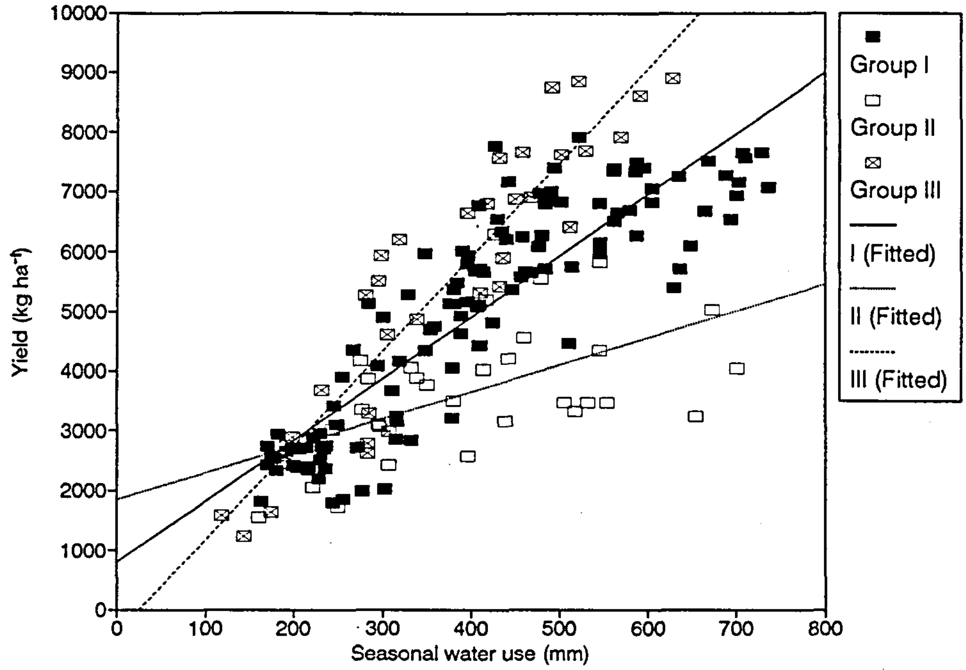


Fig. 8.5 Yield-water production functions for spring wheat (cv. SST86) at Roodeplaat (see Table 8.3 for explanation of Groups I-III and equations of fitted lines). Data points are derived from all water/nitrogen treatments in all four seasons (means from 2-4 replicates).

8.2 Nitrogen Application Rate

Nitrogen plays an essential role in the plant in the form of DNA and RNA, which are the building blocks of plant tissue (Devlin & Witham, 1983). Roots preferentially absorb nitrogen from the soil in the form of nitrate (NO_3^-), but it can also be absorbed as ammonium (NH_4^+) (Mengel & Kirkby, 1987). The plant reduces the absorbed nitrate to ammonium, whereafter it is incorporated into the carbon structure. The amount of nitrogen taken up by plants is dependent on the distribution and activity of the roots. Paramesowaran, Graham & Aspinal (1981) found that applied nitrogen increased the leaf area of wheat plants, and the resulting increase in available photosynthetic area led to an increase in yield.

It is well known that nitrogen fertilization is needed to sustain profitable yields. However, N fertilizer can be a major expense, so from an economical standpoint it plays an important role in decision-making and should be used in the most effective manner (van Cleemput, Hofman & Baert, 1981). One must be aware of the effects of nitrogen application on plant growth and development. Applying too little nitrogen will usually result in poor growth and sub-economic yields, but if an excess of nitrogen is applied this can lead to luxurious uptake of N and subsequent lush shoot growth without achieving an increased grain yield.

The main objective for using different nitrogen treatments in this project was to study the interactive effects of N and water on grain yield in order to be able to validate the crop models over a wide range of potential conditions. (Details of the nitrogen application rates used in the four wheat seasons are given in Chapter 3, section 3.4.1.)

8.2.1 RESULTS & DISCUSSION

Examples of the effect of nitrogen application rate on grain yield, from 1991 and 1992, are shown in Fig. 8.6. There was a highly significant effect of nitrogen on yield in all the experiments except for 1992 (Table 8.2; Fig. 8.6(b)). This discrepancy can largely be accounted for by the fact that the N content of the irrigation water from Roodeplaat dam increased during this season, due to the operation of a new sewage treatment works upstream of the dam. It is also possible that nitrogen was mineralized in the soil from the summer of 1990 until wheat was planted on the same site in 1992, and that not all this nitrogen was utilized by the intermediate crops (sorghum and maize) that were planted specifically to deplete the N in the soil profile.

Increasing the N application rate had no effect on yield in the drier treatments (W1 and W2) of all the experiments. Here the lack of water was the overriding factor and the N available in the soil was sufficient for the low yields obtained. However, at the higher water application levels (W3, W4 and W5) of the 1990, 1991 (both irrigation frequencies) and 1993 experiments, the yield increased in response to increased N application until the plant requirements were met, when a yield plateau was obtained (Fig. 8.6(a)). The data from all these experiments indicated that for an optimal yield to be obtained, the N application rate would need to be between 130 and 150 kg N ha^{-1}.

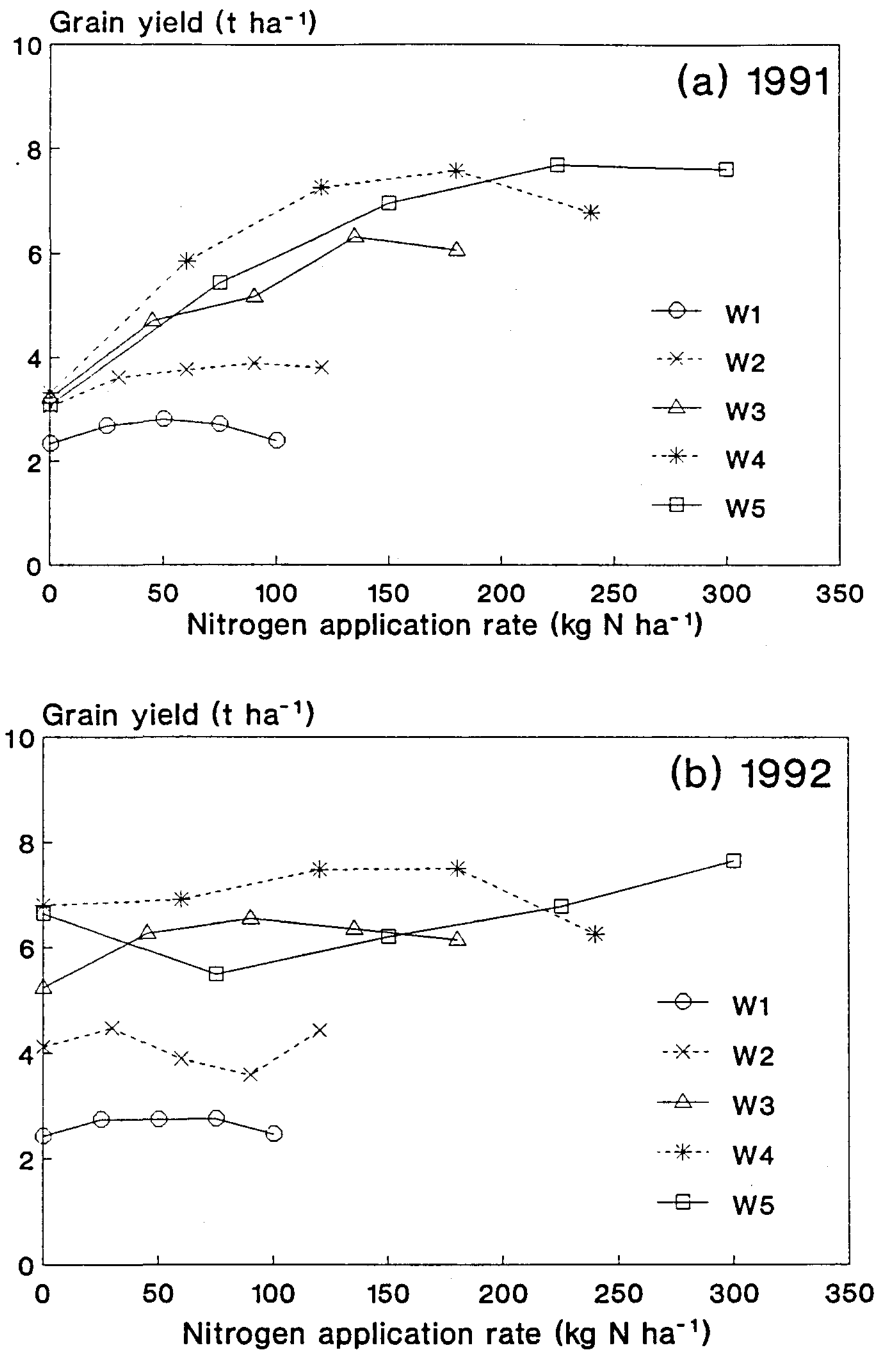


Fig. 8.6 The relationship between wheat grain yield and nitrogen application rate at each irrigation level in (a) 1991 (weekly frequency) and (b) 1992.

8.3 Guidelines for Irrigated Wheat Farmers

The data collected in this project make it possible to suggest practical guidelines for both water and nitrogen application that are acceptable to the farming community. A yield of 6-7 t ha^{-1} seems to be generally accepted as a target amongst the farmers in the Brits area. According to the yield-water production functions this would require a seasonal water use of approximately 550 mm if irrigation was applied weekly, but only 440 mm if applied once every two weeks. A optimum nitrogen application rate of 135 kg N ha^{-1} is suggested. These guidelines are, however, subject to the following points:

a) The amount of nitrogen applied is strongly influenced by the amount of nitrogen carried over from the previous season and the nitrogen mineralization capability of the specific soil.

b) The clay content of the soil plays an important part because sandy soils would be subjected to a certain amount of nitrogen leaching. In that case the nitrogen application must be split and applied on several occasions during the season, and in certain instances the amount could be increased to compensate for leaching losses.

c) It is a well known fact that in some areas farmers experience problems with lodging of the wheat crop, due to adverse conditions of wind and rain, which can lead to substantial losses. According to farmers in these areas it is a financial risk to apply more than 135 kg N ha^{-1}. This problem could be overcome by planting one of the new short-straw cultivars now available.

d) The seasonal water use will depend on both the efficiency of the irrigation system and the clay content, and therefore the water-holding capacity, of the soil. To a lesser extent factors such as changes in weather patterns, slope of the land and agronomic and management practices will also have an influence.

8.4 Yield Components

It is well known that water stress causes a significant decrease in the yield of grain crops (Aspinall, Nicholls & May, 1964). However, the final grain yield can be viewed as the product of the numbers of grains per ear and ears per m^2, and the mean individual grain mass. During different development phases the relative influence of these different yield components can be determined. According to Hay & Walker (1989) the final grain yield is more dependent on kernel number than kernel mass, except under drought conditions. They further suggested that nitrogen application with irrigation will have a greater influence on the number of ears per m^2 than on the number of kernels per ear, and that individual kernel mass is not influenced by nitrogen but is dependent on water and on kernel population density, and sickness and lodging of the crop. Water stress at critical times generally causes floret and sometimes whole spikelet death at the terminal ends of the spike/ear. Water stress during the late vegetative phase just before spike initiation adversely affects the final number of fertile florets per spike, with the reduction in fertile florets being accounted for by fewer spikelet primordia being formed. Water stress during late internode elongation prior to spike emergence resulted in death of florets and whole spikelets at the terminal and basal ends of the spike (Oosterhuis & Cartwright, 1983; Garcia del Moral, Jimenez, Garcia del Moral, Ramos, Roca de Togores & Molina-Cano, 1991).

The aims of this study were to investigate the influence of water and nitrogen on the yield components and on the number of kernels per spikelet position in the spike/ear, and to determine the extent to which each yield component influences the final grain yield.

8.4.1 MATERIALS & METHODS

Data collected included the numbers of ears per m^2 and kernels per ear, the kernel mass, and the number of kernels per spikelet position in the spike/ear. The last three values were determined from 5 ears per treatment/plot. The final measured oven-dry grain yield over all four wheat seasons was compared to yield calculated from the product of the yield components:

$$\text{Yield} = \text{no. of ears/m}^2 * \text{no. of kernels/ear} * \text{mass/kernel} \qquad [8.2]$$

To investigate the influence of different water and nitrogen applications on the yield components and kernel position, a GENSTAT multiple regression analysis was performed on the data. The Forward Selection Stepwise Regression procedure was then used to determine the degree of influence each yield component had on final grain yield.

8.4.2 RESULTS & DISCUSSION

A good correlation was observed between the calculated and measured grain yields (Fig. 8.7; $r^2 = 0.88$), although the calculated figures were generally greater than the measured ones, especially at the higher yields.

Although all three yield components showed significant differences between the water and nitrogen applications (Table 8.4), ears per m^2 had the highest percentage variance which could be accounted for, and kernel mass the lowest. Table 8.4 also shows that a year effect occurred for all the yield components, which indicates that the crop was exposed to different stress conditions during the growth stages in the four years.

The numbers of ears per m^2 (Fig. 8.8(a)) and kernels per spike both increased with increasing water and nitrogen supply. Kernel mass (Fig. 8.8(b)) also increased in response to water, but decreased as the nitrogen level increased at all the water treatments. It would appear that stress occurred during the double ridge phase when the cell division took place to form the number of kernels, or that kernels were aborted as stress conditions occurred during the late vegetative phase. There were also fewer kernels per land area in the stressed treatments due to the lower number of tillers per plant. The influence of nitrogen on kernel mass appeared to differ from that of water supply, with more carbohydrates being available to fill the kernels under the lower nitrogen applications over the range of water treatments. However, due to kernel mass having a much smaller influence than the numbers of kernels per ear and ears per m^2 (i.e. kernels per land area), this effect of N on kernel mass is not evident when one looks at final grain yield as a whole.

Table 8.4 Results of a multiple regression analysis on the effects of crop water use (WU), nitrogen application (N) and year (Y; 1990-93) on wheat yield components. [% V = percentage variance accounted for; ** $p < 0.01$; * $p < 0.05$; ns = non-significant.]

	Ears per m²		Kernels per ear		Kernel mass	
	% V		% V		% V	
WU	37.8	**	21.2	**	10.8	**
N	15.0	**	5.0	**	4.2	**
WU x N	0.1	ns	3.0	**	2.0	**
Y	2.9	**	13.8	**	7.7	**
WU x Y	0.8	ns	0.0	ns	7.9	**
N x Y	0.0	ns	0.0	ns	1.9	*

Results from the stepwise regression to determine the relative influence of each individual yield component on final grain yield are presented in Table 8.5. It is clear that the number of ears per m^2 had the largest influence on yield, with the number of kernels per ear and kernel mass having only a very small effect. This trend compares well with previous studies in the literature.

Table 8.5 Results from the stepwise multiple regression analysis on the influence of the individual yield components on final wheat grain yield (1990-93).

	Order	% Variance	Coefficient
Ears per m²	1	77.9	16.90
Kernels per ear	2	3.3	40.84
Kernel mass	3	1.4	30.80

There was a significant effect of water and nitrogen on the number of kernels per spikelet in the middle and top sections of the spike/ear (Table 8.6). The effect of inadequate water or nitrogen was to reduce the kernel number by a similar magnitude at most positions on the spike. The year effect also played a role in all the spikelet positions, probably due to temperature, water or nitrogen stress occurring at different times during the growth stages in each season.

Table 8.6 Results of a multiple regression analysis on the effects of crop water use (WU), nitrogen application (N) and year (Y; 1990-93) on the number of kernels per spikelet position in the spike/ear. [TopL, TopM and TopH refer to the lower, middle and highest sections of the top part of the spike; ** $p < 0.01$; * $p < 0.05$; ns = non-significant.]

	Bottom	Middle	TopL	TopM	TopH
WU	ns	**	**	**	**
N	ns	**	**	*	**
WU x N	**	*	**	**	ns
Y	**	*	**	**	**
WU x Y	ns	ns	ns	ns	**
N x Y	ns	ns	ns	ns	ns

8.4.3 CONCLUSION

The increase in yield due to water and nitrogen applications can be mainly attributed to the component of the number of ears per m^2, with the number of kernels per ear and the kernel mass having a much smaller influence. There was a significant effect of both water and nitrogen on all the yield components and on the number of kernels per spikelet position in the spike/ear.

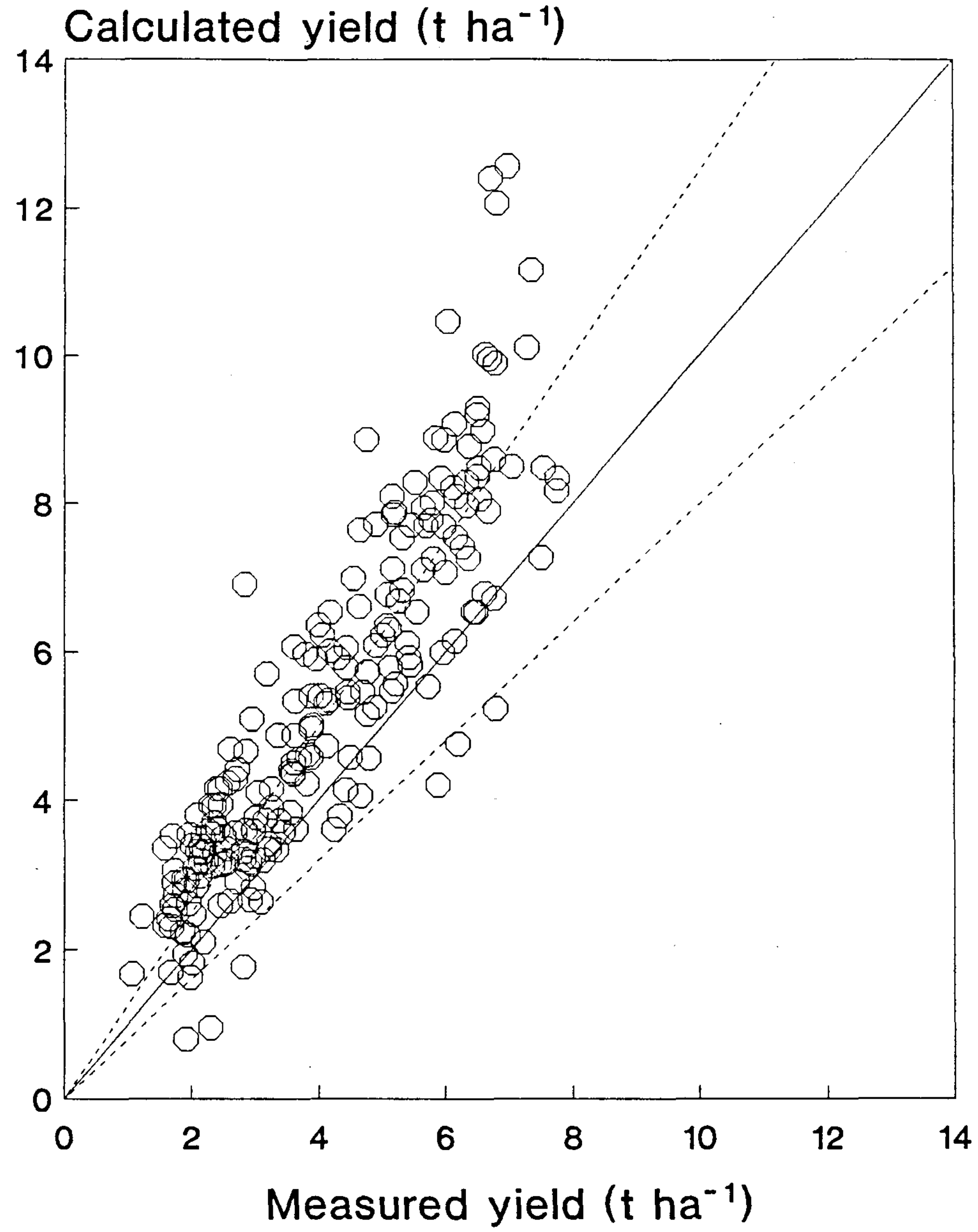


Fig. 8.7 Comparison between the yield calculated from yield components and that recorded in the field during the four wheat seasons.

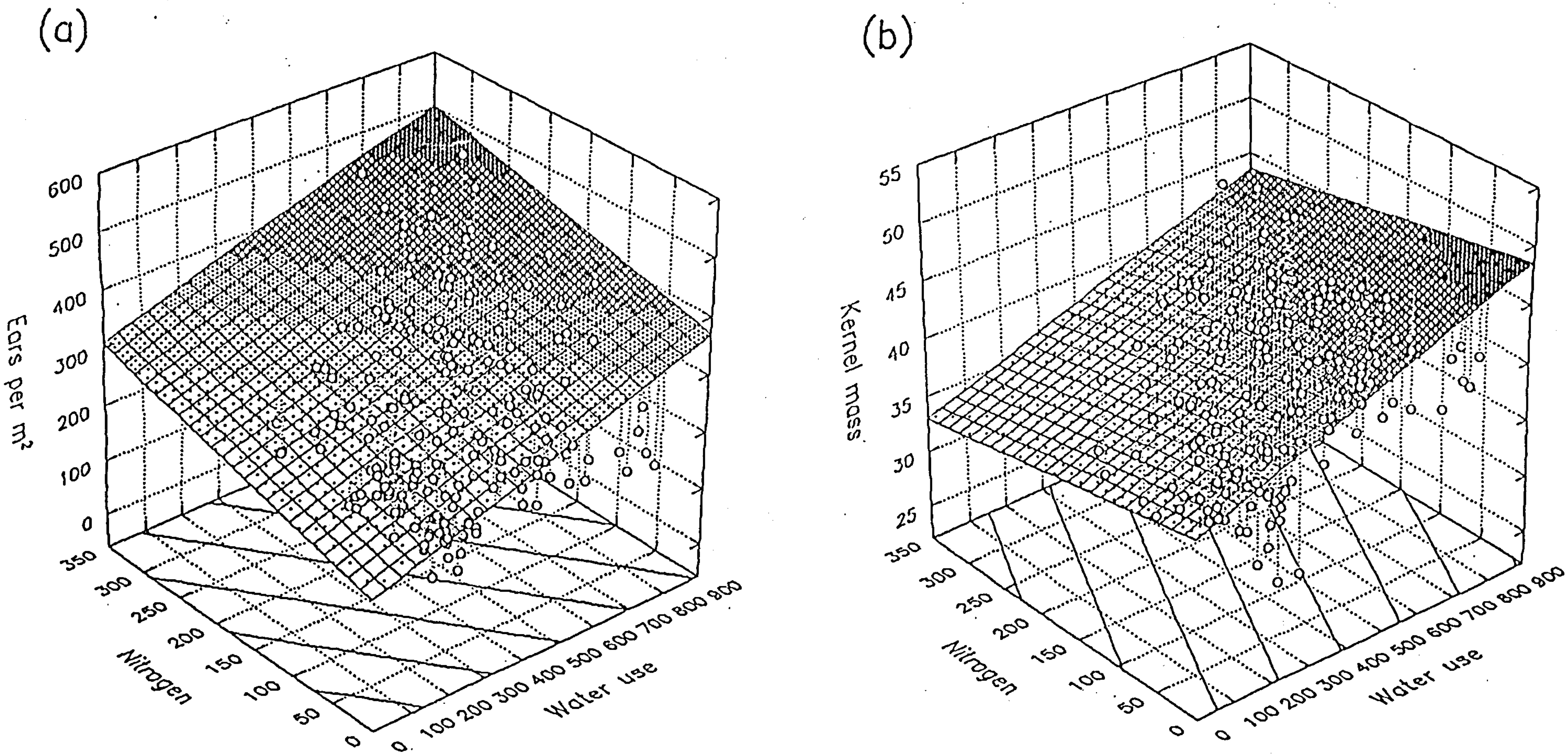


Fig. 8.8 The influence of water use (WU) and nitrogen application (N) on (a) number of ears per m², and (b) kernel mass during the four wheat seasons. The equations for the response surfaces are (a) Ears per m² = 175.8 + 0.379WU + 0.216N, and (b) Kernel mass = 38.05 + 0.0117WU - 0.0145N.

8.5 Conclusion

A large and comprehensive dataset was obtained during this study of the effects of different water and nitrogen application levels on wheat yield. Linesource experiments were carried out in all four years, each comprising 25 water/nitrogen treatment combinations, and at two irrigation frequencies in 1990 and 1991.

This dataset allowed grain yield-water use production functions to be determined for spring wheat cv. SST86 under Roodeplaat conditions. The slope was reduced by a lack of added nitrogen but increased when irrigation was applied every two weeks instead of weekly. This more efficient use of water by the crop would mean more economic irrigation for the farmer. For example, the data shows that for a target grain yield of 6-7 t ha^{-1}, a seasonal water use of approximately 550 mm would be required if irrigation was applied weekly, but only 440 mm if it was applied once every two weeks.

At the higher water application levels, crop yield improved with increasing nitrogen application, but an exception occurred in 1992 when a higher N content in the irrigation water meant that no treatment differences were obtained. An optimal application rate for nitrogen fertilizer of 135 kg N ha^{-1} is suggested for a 6-7 t ha^{-1} target yield.

The recommendations for farmers hold true for a deep soil with a high clay content such as a Hutton, in the warm irrigation area with spring wheat cultivars. The actual requirements for a specific farm will need to be adapted from these guidelines, based on a recent soil analysis and a consideration of the local weather conditions and recommended cultivars. Further research is necessary to investigate the optimal levels of irrigation and fertilization for newly released cultivars that are especially adapted to this area. Some of these cultivars may be expected to have a lower water requirement if there is a significant difference in the height of the crop and the length of the growing season.

Chapter 9

BEWAB IRRIGATION SCHEDULING PROGRAM

BEWAB is an irrigation scheduling program developed by Prof. A.T.P. Bennie and co-workers at the University of the Orange Free State (Bennie, Coetzee, van Antwerpen, van Rensburg & Burger, 1988). It is written using the GW-BASIC language and is very user-friendly, making it simple for the irrigation farmer or extension officer to use. In BEWAB, irrigation is scheduled for a specific target yield using a water balance method, with the daily crop water requirement determined from a yield production function. The concepts of profile available water capacity (PAWC) and a stress index are also included. The water in the soil profile is managed so that it is partially replenished early in the season in order to prepare for peak water use. The program allows for various soil-crop combinations as well as a choice of management options relating to the initial and final profile soil water contents (see example printout in Appendix 3).

One of the main objectives of this project was to test the reliability of the BEWAB irrigation scheduling program under a range of water-nitrogen regimes. Since the program was used in all four wheat seasons at Roodeplaat, a large and comprehensive dataset was obtained with which to do this. Information from an irrigated wheat farmer was also used in assessing the performance of BEWAB.

9.1 Evaluation of the BEWAB Program at Roodeplaat

Details of how BEWAB was used to schedule irrigation in the wheat experiments, for a target yield of 8 t ha^{-1}, were given in Chapter 8. The program was then tested by comparing the measured crop water use with the amount predicted for the actual yields obtained at the different water application levels.

9.1.1 MATERIALS & METHODS

The derivation of the yield-water production functions was described in Chapter 8, section 8.1.2. Data points from the majority of the weekly irrigated treatments where nitrogen was added fell along a line with a slope equal to 10.25 kg ha^{-1} mm^{-1} (Group I in Chapter 8, Table 8.3 and Fig. 8.5). Using this data, the mean crop water use was calculated for each water application level (W1-W5), and the corresponding yield determined from the production function. BEWAB was then run with this as the target yield, and the final total for the predicted "complete crop water demand" on the BEWAB printout (Appendix 3) was compared with the observed seasonal crop water use. Further tests included using the measured PAWC of 163 mm (see Chapter 8, section 8.1.2) as an input instead of allowing BEWAB to calculate a value from % silt + clay data, and replacing root growth coefficients in the program with measured values.

9.1.2 RESULTS & DISCUSSION

Table 9.1 gives the target yield for each water treatment and compares the predicted and observed seasonal crop water use totals (D-value simulation index = 0.96). As expected, the predicted values are consistently higher because the slope of the production function used by Bennie *et al.* (1988) for spring wheat in BEWAB is 11.38 kg ha^{-1} mm^{-1}, slightly higher than the value of 10.25 kg ha^{-1} mm^{-1} determined in this project for most weekly irrigated treatments supplied with nitrogen. The program could now be adjusted for Roodeplaat conditions, and if the production function coefficients are indeed changed then the predicted water use for W5 becomes 645 mm, compared with the 648 mm observed. Clearly if one was to undertake a similar test using data from the N0 treatments or those with adequate N but irrigated every two weeks, where the production function slopes differed even more from the BEWAB figure, the crop water use estimates would be even further out.

The complete crop water demand totals estimated by BEWAB were unaffected when the measured PAWC of 163 mm was used instead a calculated value. However, the irrigation scheduling figures required when starting with a full profile and ending with a dry one did change. Table 9.1 shows that a different PAWC was estimated by BEWAB for each target yield, with the value decreasing as yield increased. This led to a considerable underestimation of PAWC at the W5 target yield of 7.4 t ha^{-1}. The reason for the change in PAWC is that the higher the target yield, the higher the crop water demand that BEWAB predicts. The plants will therefore become stressed quicker. Since the soil profile supply rate is a function of the profile water content, BEWAB calculates that a lower amount of water can be withdrawn from the root zone before the plants become stressed (the definition of PAWC given by Bennie *et al.*, 1988).

The amount of root growth predicted by BEWAB also influences the calculated PAWC. Amongst the root growth coefficients in the program are a root growth rate (RGR) of 17.7 mm d^{-1} and a maximum root length index (RLI) of 5.33 mm mm^{-2}. Core sample data from the 1991-93 wheat experiments gives equivalent mean values of 14.9 and 3.22 respectively. If these measured figures are included in the BEWAB program then the estimated PAWC for W5 drops from 116 to 77 mm. The practical effect of the slower rate of root system development will be that a larger amount of irrigation will be needed each week to compensate for the lower PAWC.

Table 9.1 Target yield and measured crop water use for each water treatment, with the calculated water use and PAWC values determined by BEWAB.

	Target yield (kg ha^{-1})	Crop water use (mm)		Calculated PAWC (mm)
		Observed	Predicted	
W1	2834	199	278	174
W2	3926	305	373	161
W3	5126	422	478	147
W4	6341	541	584	133
W5	7439	648	680	116

9.1.3 CONCLUSION

Considering that the BEWAB irrigation scheduling program was developed for wheat in the Orange Free State, its performance under Roodeplaat conditions was quite good. However, if it is to be used extensively in the warm irrigation area then the crop water requirement coefficient should probably be changed to suit the warmer and earlier spring, which results in a higher evaporative demand. The data recorded in this project could be used to make such an improvement, and to test other components of the BEWAB program. This may result in recommendations for changes such as broadening some of the ranges that are allowed for specific variables under these warmer conditions.

9.2 Practical On-farm Application

From the beginning of this project it has always been kept in mind that the modern irrigated wheat farmer must receive some benefit from the experimental results. Therefore the cultivation methods and agronomic practices were kept simple and comparable to those used by wheat farmers in the Magaliesburg district. The research findings should also be evaluated in a practical on-farm situation, under the normal constraints placed on a farm operation. Part of the strategy for testing the reliability of BEWAB was to evaluate the irrigation scheduling program from a practical standpoint, that is from the point of view of the farmer.

Initially, one needed access and first-hand experience of general problems encountered in farm irrigation. The research team used the following channels:

a) Regular attendance at farmer information days, both as visitors and presenting lectures.

b) Collaboration with extension officers, employees of farmer co-operatives, and the Small Grain Centre at Bethlehem.

c) A farmers day held at the ISCW Roodeplaat research terrain in 1993 on various aspects of wheat production.

d) A case study conducted on a farmer's wheat field in the Brits area.

After working with the farming community the following problems were identified:

a) Poor water quality from both dams and boreholes, with the emphasis on salinity and chloride pollution.

b) Problems concerned with the reliability and dependability of water supply.

c) Poor irrigation scheduling due to a lack of information and the physical incapabilities of the irrigation system.

d) Poor maintenance of irrigation systems resulting in excessive wear and tear leading to failures and uneven distribution of irrigation water in the field.

At least one of these issues could be addressed by the application of the BEWAB program under farm conditions to assist in streamlining the irrigation scheduling. An on-farm test of the BEWAB program was not possible, but the soil water content under the current irrigation schedule was monitored in the wheat fields of two farmers in 1993. Unfortunately, one of the farmers had a problem with a pump breakdown and so only the one situation will be discussed.

9.2.1 MATERIALS & METHODS

The practical case study in the Brits area involved the measurement of the weekly amount of irrigation as well as monitoring the soil water content with a neutron probe. The specific farmer is regarded as economically productive with a substantial knowledge of irrigation practices. The motivation for the involvement was to assess the irrigation scheduling of the farmer and compare the end results with a simulation from the BEWAB program. The yield (approximately 5 t ha^{-1}) was obtained from the farmer, together with the other information needed to run the program. The actual weekly and cumulative irrigation totals were then compared with the BEWAB predictions.

9.2.2 RESULTS & DISCUSSION

The irrigation predictions given by the BEWAB program are regarded as a good practical norm which had proved to be trustworthy for use by our research team throughout this project. Fig. 9.1(a) indicates that too much water was applied by the farmer during the first 50 days after planting. The possible rationale behind this was to fill the profile in order to provide for peak-time water consumption. However, in this case there were probably losses due to deep drainage. It is also evident that the farmer started to reduce the weekly application at around 85 DAP, which is too early since the plants only go into anthesis at about 95 DAP. As our team members visited the site regularly it was visually noted that the plants were subjected to a certain degree of stress during this period, and these observations were also evident from the data collected.

Another weak point in the farmer's scheduling programme was that he stopped irrigating 4-5 weeks too early. This was during the grain-filling period which is considered to be one of the critical periods in the life cycle of the crop. However, in this specific year, nature saved the farmer from a potential disaster as over 100 mm of rain fell during that growth stage and so stopping the irrigation did not in fact affect the final yield.

The wheat crop received 574 mm of water, including the effective rainfall and irrigation applied by the farmer, in contrast to the 467 mm predicted by BEWAB for a target yield of 5 t ha^{-1} (Fig. 9.1(b)), so the farmer applied over 100 mm more water than was necessary. It is therefore reasonable to come to the conclusion that if the farmer were to change his irrigation scheduling programme he could possibly stretch his water supply to a larger piece of land and still obtain the same yield within safe limits (allowing for plant stress during hot spells).

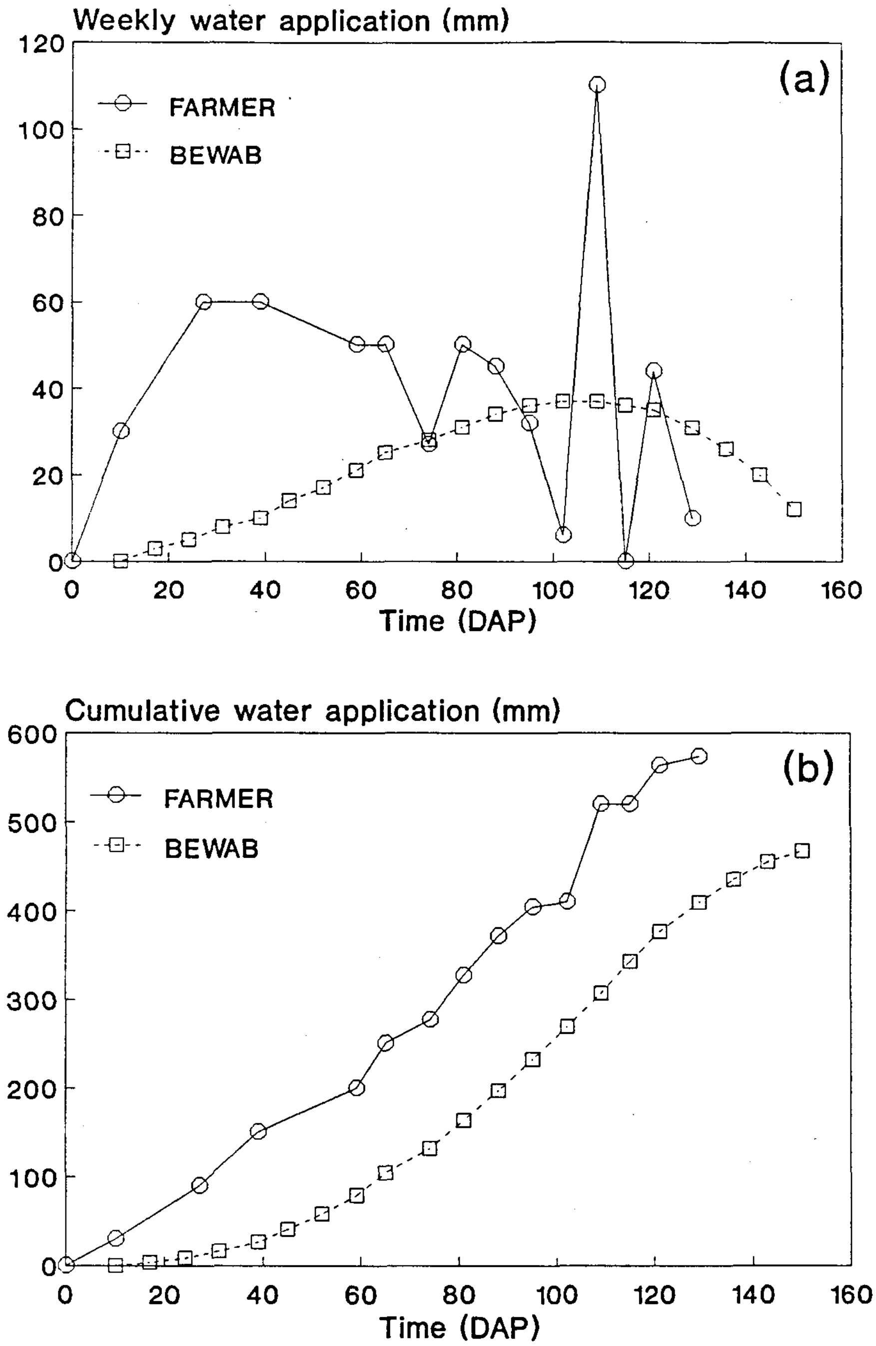


Fig. 9.1 Comparison between water applied to the wheat crop by the Brits farmer (including rainfall) and the irrigation schedule predicted by BEWAB, on a (a) weekly and (b) cumulative basis.

9.3 Conclusion

The objective to test the reliability of the BEWAB irrigation scheduling program under the different water-nitrogen regimes, particularly in connection with the water use, water use efficiency and yield predictions, has been successively achieved. Information from the linesource field experiments at Roodeplaat during the four wheat seasons has shown that BEWAB can predict the irrigation for spring wheat varieties in the warm irrigation area quite well, even though it was developed for winter varieties in the cool irrigation area. However, based on this information, adjustments in the program could now be made in order to improve its performance.

It appears that farmers in the Magaliesburg district would be able to improve their irrigation efficiency, and either save water and pumping costs or irrigate a larger area of land, if they were to use the BEWAB program to plan their irrigation scheduling.

Chapter 10

CROP GROWTH MODELS

There are many models available that have been developed for a variety of purposes and therefore represent different levels of complexity and can be used for different requirements. The scope of the models discussed in this study include those that try to simulate the crop growth and water use, and finally give a prediction of the crop yield. The initial aim was to select several typical crop growth simulation models and test them for wheat grown under South African conditions at a range of water and nitrogen treatments. The next step was to recommend modifications, where necessary, in order to adapt the models to South African conditions. To achieve these aims a literature review was conducted, and personal contact was made with several of the authors of the various models. The models were then calibrated using field data collected during this project. The validation of the models was conducted using independent datasets that had not been used for the calibration.

The models selected for this study were CERES-wheat version 2.10, PUTU-wheat versions 991 and 992, and SHOOTGRO-wheat version 4. CERES was developed by an international and interdisciplinary team of scientists with Dr. J.T. Ritchie as coordinator (Hodges & Ritchie, 1991). PUTU was developed under South African conditions by Prof. J.M. de Jager, Dr. A. Singels and co-workers from the University of the Orange Free State, Department of Agrometeorology (Singels & de Jager, 1991b). SHOOTGRO was developed by G.S. McMaster, W.W. Wilhelm, R.W. Rickman, B. Klepper, J.A. Morgan and co-workers in the USA (McMaster, Morgan & Wilhelm, 1992; McMaster, Wilhelm & Morgan, 1992; Wilhelm, McMaster, Rickman & Klepper, 1993).

10.1 Literature Review

There are many models available that deal with agronomic crops, but if they are to be close to the real life situation, they must have a good simulation of the actual growth and development of the crop. The specific purpose of the literature review was to investigate the growth section which deals with the phenology and biomass accumulation in wheat growth models. Although each model has certain cultivar-specific parameters, the basic theory behind the logical driving forces will be discussed for the following:

(i) The O'Leary wheat model (O'Leary, Connor & White, 1985) was developed in Australia as part of a project designed to study various management options to increase production under rainfed agriculture. It is intermediate in complexity and the phenology submodel forms the framework for the biomass allocation and accumulation of yield.

(ii) CERES is an acronym for Crop Estimation through Resource and Environment Synthesis. The crop growth simulation section is divided into phasic development which represents the phenology, and growth and organ development which is the biomass accumulation. Basically a carbon balance is carried out through the season.

(iii) PUTU-wheat was developed in Bloemfontein for spring wheat. It simulates the phenological and leaf expansive growth, including effects of temperature and water stress.

(iv) SHOOTGRO was developed for winter wheat in the Central Great Plains of the USA. It describes the above-ground growth and development of wheat, including leaf and tiller appearance based on thermal time and phyllochrons.

10.1.1 PHENOLOGY

In the O'Leary model the phenology is driven by the sum of the photothermal units, which are a combination of the heat units and daylength. Certain important phenological switches, namely emergence, beginning of stem extension, booting, anthesis and maturity are used to change critical factors in the rest of the model, particularly in the water balance and growth subsections (Table 10.1). The sowing to emergence phase is only controlled by the thermal units above 3.0°C, and the switch is activated when a certain amount (78.0) has been accumulated. From emergence until the commencement of stem elongation, thermal units are calculated above 4.0 °C, until another set total (315.0) is attained. The phenological switches from stem elongation to booting and anthesis are both driven by photothermal units, with the total number being highly cultivar-specific. Thermal units are used to describe the grain-filling phase from anthesis to maturity. During the stem extension phase the leaf senescence begins at a rate of 0.3 % per day. Then the rate of senescence increases at booting (0.8 %) and after anthesis it is dependent on thermal units, until finally at maturity the leaf area is again zero. There is a change in the rate of root exploration of the soil when stem extension begins, and root growth ceases at anthesis.

In CERES-wheat the phenology is divided into 9 stages, which include fallow and sowing to germination stages which do not deal with the plant as such (Ritchie, 1986). These stages are controlled by thermal units, and a base of 0°C is used throughout with a maximum of 26°C. The phyllochron concept is used, whereby a thermal time per leaf is calculated and used for switching to certain stages. The time to emergence is dependent on the temperature and depth of sowing (Table 10.1). A cultivar specific vernalization factor (50 days between 0 and 7°C) is included in the vegetative phase to accommodate the winter wheat cultivars. The leaf growth is dependent on thermal time (400 degree-days, dd), and phyllochron number which is an input in the model. From pre-anthesis until the beginning of the grain-filling period is 200 dd after fertilization. Then a further 500 dd are allowed from anthesis for the grain-filling period.

The phenological sub-model of PUTU is similar to CERES-wheat in that several growth stages are represented. There is a maximum rate of development which is then reduced by various environmental control factors. The basic driving force is through the thermal time with a base temperature of 2.8 °C. A daily vernalization is also included which is based on the mean daily temperature (Singels & de Jager, 1991b).

Table 10.1 A comparison of the factors affecting the various phenological switches in the O'Leary and CERES-wheat models, where TU is thermal units at the specified base temperatures; PTU is the photothermal units which include day length; PHY is a phyllochron (the thermal time between each leaf appearance); and PAWC is the plant available water capacity.

PERIOD	O'LEARY	CERES	PARTS GROWING
Pre-plant		PAWC	none
To germination	TU>3°C	TU>0°C	none
To emergence	TU>3°C	TU>0°C; depth	root; coleoptile
To stem extension/spike initiation			
To boot	TU>4°C	PTU=400	root; leaf; stem
To end of pre-anthesis	PTU>4°C	TU; PHY=3	root; leaf
To start of grain-filling			
To grain-filling	PTU>4°C	PTU; PHY=2	root; leaf; ear
To maturity			
	PTU>2°C	TU=200	root; stem
	TU>8°C	TU(>1°C)=500	root; stem; grain
	TU>8°C		grain

SHOOTGRO makes use of calendar days, thermal and photothermal units. For winter wheat a base temperature of -2.0 °C was best and an optimal temperature of 25 °C was used. For the period from emergence through tiller initiation to jointing, the regular calendar days gave the best relationship. Following this through the grain-filling period, photothermal units were used (McMaster & Smika, 1988).

10.1.2 BIOMASS ACCUMULATION

In the O'Leary model, the biomass accumulation is estimated from the water production function, where a certain biomass is accumulated per unit of water transpired (Hanks, 1974). The leaf area index is calculated from the relative growth rate method (Charles-Edwards, Doley & Rimmington, 1986) using the leaf area ratio (LAR, ha kg^{-1}) which has been calculated from the thermal units (with a base of 4.0 °C) accumulated since planting. The LAR also changes with the stem extension switch. Once the amount of biomass accumulated per day is calculated, it must be divided into above- and below-ground accumulation. The partitioning to the roots is controlled by the mean daily temperature in a parabolic function. The depth of root penetration is dependent on the thermal units above 4.0 °C until anthesis. The effect of limited soil available water is included as a scaling factor. The partitioning to the grain-filling begins at anthesis and is calculated from grain number and maximum grain size which are both cultivar-specific. The maximum grain growth rate is also temperature dependent, although it does change through the grain-filling period. Pre-anthesis assimilates in the final grain yield are limited to 10% of the total biomass at anthesis.

In CERES-wheat, potential biomass accumulation is driven by the photosynthetically active radiation (calculated from solar radiation) intercepted by the plant (Monteith, 1977). The amount intercepted is dependent on the leaf area index of the crop, which comes from the calculation of daily leaf expansion. Water and high temperature stress factors reduce the biomass production rate. The leaf area is increased as a linear function of temperature (between 0 and 26 °C) and the phyllochron. The area to weight ratio is used to convert to potential leaf growth in terms of assimilate. The root growth is then the difference between the total biomass accumulated and that used by the leaf growth. The tillers are produced according to the leaf number (Klepper, Rickman & Peterson, 1982). Senescence is coupled to the leaf development, as only 4 or 5 full leaves may be present at any one time. It is dependent on the leaf biomass present and the accumulated thermal time. Partitioning is dependent on the present root/shoot ratio and the soil water deficit function. During the initial vegetative stage a larger proportion of the biomass accumulated goes to the leaves, but after stem elongation begins, it is partitioned almost equally, until pre-anthesis growth of the ear also receives a portion. The number of kernels is cultivar dependent and calculated from the total biomass of the stem and ear at the beginning of grain-filling period. The thermal time for the grain-filling period is also genetically controlled. Root growth ceases during this period. A dynamic feedback mechanism is used for the partitioning at this stage. The grain-filling rate is calculated as a function of temperature between 0 and 17 °C, and another genetic coefficient. The root length density is calculated from the amount of biomass partitioned to the roots (Gregory, McGowan, Biscoe & Hunter, 1978). The downward development is a function of thermal time and water stress factors.

In PUTU a daily leaf growth per plant is used together with plant population and crop age factors. The driving force for the biomass accumulation is from the intercepted radiation. The daily leaf expansion rate is then calculated from the existing leaf area index. A function is included for inter-leaf competition by only allowing a certain number of leaves to grow. Senescence is calculated as a percentage of the leaf area at anthesis (Singels & de Jager, 1991b). Factors are included for temperature and water status effects.

In SHOOTGRO, leaf area is simulated by increasing the length and width of individual leaves on the culm. The rate of expansion is controlled by the maximum value divided by the phyllochron in thermal time. The leaf weight is then a constant multiple of the leaf area and leaf sheaths make up a certain proportion of the leaf material. Leaf senescence begins after a set number of phyllochrons (Wilhelm, McMaster, Klepper & Rickman, 1990). SPIKEGRO then simulates the growth and development of the shoot spikelet primordia, florets and kernels, being driven by the daily maximum and minimum temperatures. The growth stages from single ridge through anthesis are based on the number of phyllochrons, which varies with the change in daylength at emergence. The model simulates yield per land area, but also on a plant, culm, spikelet and kernel basis (McMaster, Wilhelm & Morgan, 1990).

10.1.3 SUMMARY OF COMPARISON OF MODELS

The main driving force of temperature together with some photoperiod effect is similar throughout the models. The phyllochron concept appears to be a good method for representing the growth of leaves or other organs. The specific values for the switches or turning points for particular cultivars can then be found. The use of intercepted radiation as the basis for biomass accumulation is a sound theoretical one and works well in the models, together with a standard conversion to leaf area and grain yield.

10.2 Input Data and Calibration of Models

It is critical that the correct input data are used to test the models properly. Inputs include weather and soil data, and some plant-specific parameters. The soil, root and phyllochron interval data will be discussed in detail.

10.2.1 SOIL DATA FILE

This file includes the soil water-holding capacity values for the lower limit (LL) and drained upper limit (DUL). Use of the correct LL and DUL soil water content values in the soil input file is of critical importance in order for the models to accurately simulate the water balance, and therefore also the wheat growth and development. A DUL of 458 mm to a 1.8 m soil depth and a LL of 295 mm were estimated as described in Chapter 8. The optimal plant available water capacity (PAWC) to a 1.8 m soil depth would therefore be 163 mm. The LL, DUL and PAWC values per layer, as used in the models, are presented in Table 10.2.

Table 10.2 The soil water-holding capacity values for the lower limit (LL), drained upper limit (DUL) and plant available water capacity (PAWC) for the different soil layers.

Soil depth (mm)	LL (%)	DUL (%)	PAWC (%)	PAWC (mm)
0 - 150	4.0	22.7	18.7	28.0
150 - 300	7.0	25.1	18.1	27.2
300 - 600	17.0	26.0	9.0	27.0
600 - 900	16.0	26.8	10.8	32.4
900 - 1200	16.0	25.7	9.7	29.1
1200 - 1500	21.0	27.3	6.3	18.9
1500 - 1800	23.0	23.2	0.2	0.6
TOTAL				163.2

10.2.2 ROOT DATA

Both PUTU and SHOOTGRO have an exponential equation built in for calculating percentage roots distributed over the soil profile (Ritchie, 1986). For CERES the root distribution per soil layer is an input. The ability of CERES to simulate yield using different root distribution input data was tested. Measured root data from low and high water treatments was used (see Chapter 7, section 7.2), and the root distribution calculated by an exponential equation as suggested by Ritchie (1986). However, no difference in yield was simulated using different root distributions inputs, so it was concluded that the equation of Ritchie (1986) can be used when planting at a row spacing of 25 cm, as was used for the wheat experiments in this project.

10.2.3 PHYLLOCHRON INTERVAL

The phyllochron interval (PHINT) is needed as an input value for CERES to calculate developmental durations and for SHOOTGRO to be calibrated for spring wheat cultivars. PHINT is the number of degree-days between the appearance of consecutive leaf tips; in other words it is the heat accumulation requirement to develop a leaf. During 1990 and 1992 two methods were used to collect field data to calculate the PHINT value. The first method was the measurement of leaf lengths each weekday, which was done in both years for cv. SST86. The second method (used only during 1992) was to record the Haun-index once a week in a separate trial with the following cultivars: SST44, SST66 and SST86 (Haun, 1973). The number of visible leaf tips was plotted against the cumulative heat units on that day. The inverse of the slope of this regression line is the PHINT value. Fig. 10.1 shows the data obtained during 1990 (Thackrah, Walker & McDonald, 1992). The calculated PHINT values for the different cultivars over the two years are presented in Table 10.3.

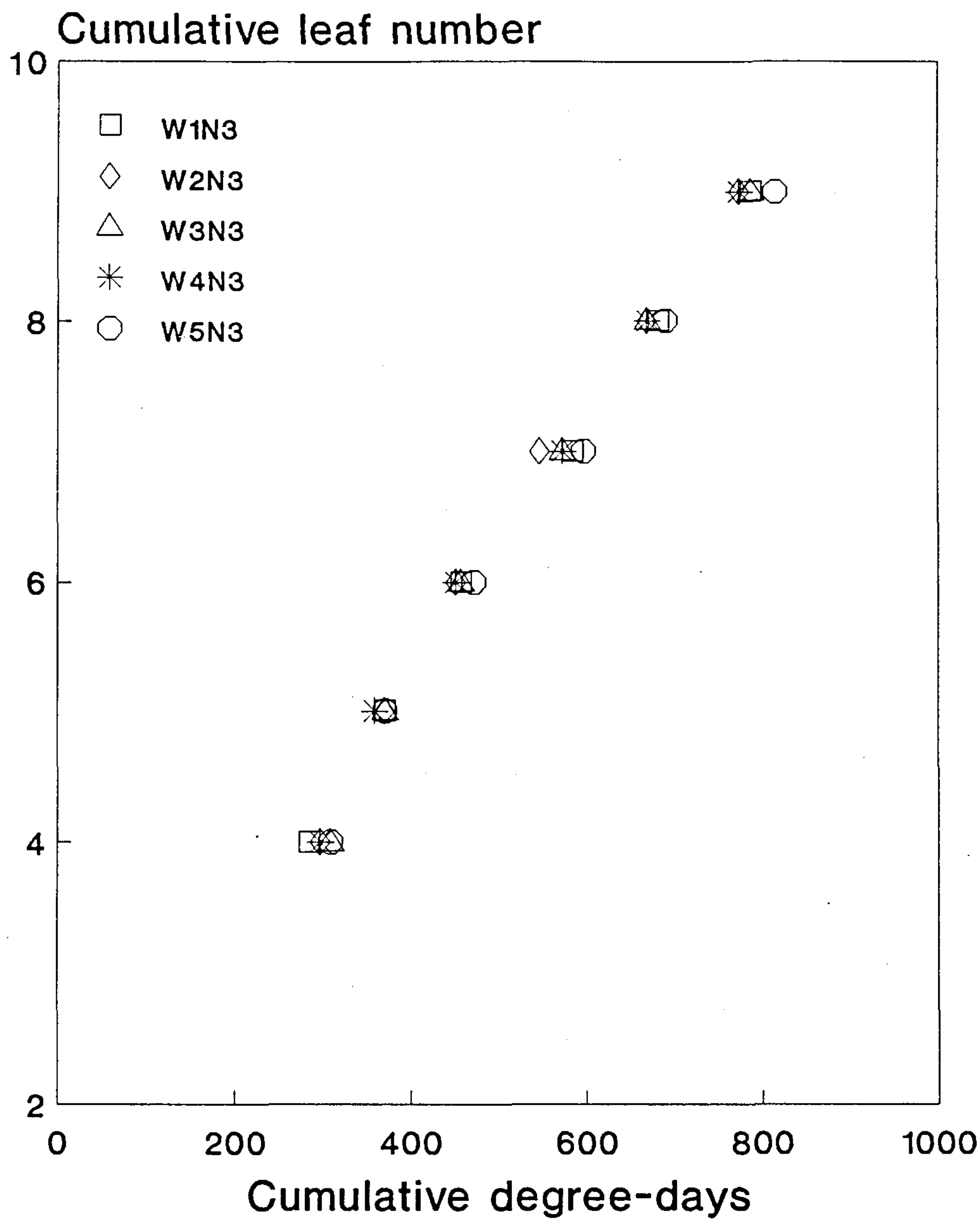


Fig. 10.1 Cumulative leaf numbers plotted against the cumulative degree-days for leaf length data collected during 1990 from increasing water and optimal nitrogen treatments (W1N3-W5N3) at Roodeplaat. A PHINT value of 100.66 degree-days per leaf was calculated from the inverse of the slope of the regression line drawn through this data (y = 0.009934(x) + 1.26; 1/0.009934 = 100.66).

Table 10.3 PHINT values as calculated for cv. SST86, SST66 and SST44 under different water and nitrogen treatments during 1990 and 1992, with the correlation coefficient (r^2) of the linear regression.

(a) 1990 SST86

TREATMENT	PHINT	r^2
W1N3	102.62	99.7
W2N3	97.49	98.9
W3N3	98.34	99.1
W4N3	99.04	99.3
W5N3	100.66	99.3
Mean	100.66	99.0

(b) 1992 SST86

	Physiology plots				Cultivar trial	
	Leaf length		Haun method		Haun method	
TREATMENT	PHINT	r^2	PHINT	r^2	PHINT	r^2
W1N0	89.45	97.6	108.62	97.0	98.23	98.2
W1N3	95.93	96.4	107.58	97.0	99.16	97.7
W3N0	103.18	95.2	113.82	95.3	108.09	96.1
W3N3	102.65	95.3	112.33	96.8	109.00	97.6
W5N0	103.98	95.8	110.96	97.0	107.45	96.9
W5N3	104.80	95.2	114.23	96.0	106.61	97.0
Mean	100.00		111.26		104.76	

(c) 1992 SST66 and SST44

	SST66		SST44	
TREATMENT	PHINT	r^2	PHINT	r^2
W1N0	97.74	96.9	103.55	96.1
W1N3	101.38	96.8	106.21	96.4
W3N0	101.49	95.7	107.28	96.8
W3N3	101.21	96.4	106.51	96.2
W5N0	101.63	94.9	103.79	95.2
W5N3	103.06	96.7	91.57	97.7
Mean	101.09		103.16	

The PHINT values for SST86 calculated from the measurements of leaf length during 1990 and 1992 compare favourably with each other, at 100.66 and 100.00 degree-days per leaf respectively. The PHINT values calculated from the two different types of measurements during 1992 for SST86, showed a difference of 4 to 10 degree-days per leaf (Table 10.3(b)). This can be explained by the different frequency of the different type of measurements. PHINT values of 101.09 and 103.16 were calculated for SST66 and SST44 respectively. With the exception of SST44, PHINT values decreased as the treatments changed from optimal water to stress conditions. From this data it seems that stress shortened the developmental duration of the plant, since each leaf would have a shorter growth duration.

10.2.4 CALIBRATION OF CERES-WHEAT

The calibration of a model is important when adapting it for an unknown cultivar. Different cultivars are developed to have optimal growth under different soil and climate conditions, and genotype coefficients are used by the model to simulate these differences. Two approaches were followed to obtain the genetic coefficients needed in the genetic input file for cv. SST86: (a) a method advised by the International Fertilizer Development Center (1989), used for CERES-WHEAT V 2.10 , and (b) to use the GENCALC (Genotype Coefficient Calculator) program developed by the IBSNAT group (Hunt, Pararajasingham, Jones, Hoogenboom, Imamura & Ogoshi, 1993; Hunt & Pararajasingham, 1993) for WHCER20S. CERES-WHEAT V 2.10 and WHCER20S are basically the same except for the format of the genotype coefficient file. [CERES-WHEAT V 2.10 (Ritchie, Singh, Godwin & Hunt, 1989a) together with CERES-MAIZE V 2.10 (Ritchie, Singh, Godwin & Hunt, 1989b), PNUTGRO V 1.02 (Boote, Jones, Hoogenboom, Wilkerson & Jagtap, 1989) and SOYGRO V 5.42 (Jones, Boote, Hoogenboom, Jagtap & Wilkerson, 1989) were modified so that the models could utilize a standard genotype coefficient file and put out a standardized OVERVIEW.OUT file.]

(a) The genotype coefficients calculated by this method using the optimal water and nitrogen data obtained during 1990 are presented in Table 10.4(a).

(b) To determine the genetic coefficients for cv. SST86 using GENCALC, the optimal water and nitrogen treatment of the 1993 experiment was used. The genetic coefficients calculated are presented in Table 10.4(b). The methodology and the use of this program are described in detail in the user manual (Hunt & Pararajasingham, 1993).

Table 10.4 Genotype coefficients for cv. SST86 as calculated by (a) the trial and error method for CERES-WHEAT V 2.10, and (b) the GENCALC program for WHCER20S.

(a)

Abbreviations used in CERES-WHEAT V 2.10	cv. SST86 values
GROWTH ASPECTS	
G1	2.8
G2	2.3
G3	2.3
DEVELOPMENT ASPECTS	
P1V	0.0
P1D	0.6
P5	16.0

(b)

Abbreviations used in WHCER20S	cv. SST86 values
BIOM	0.8497
GNUM	38.2100
GGRO	3.0860
GNUS	1.0090
DESV	0.0030
DESP	0.0037
DUGF	673.0000

Definitions of CERES-WHEAT V 2.10 genetic coefficient abbreviations:

P1V: Relative amount that the development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization are sufficient for all cultivars.

P1D: Relative amount that the development is slowed when plants are grown in a photoperiod 1 hour shorter than the optimum, which is considered to be 20 h.

P5: Degree-days above a base of 1 °C from 20°C days after anthesis to maturity.

G1: Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (g^{-1}).

G2: Kernel filling rate under optimum conditions (mg day^{-1}).

G3: Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g).

Definitions of WHCER20S genetic coefficient abbreviations:

BIOM Biomass accumulation adjustment factor (no units)

GNUM Grain number coefficient (no. g^{-1} stem weight at anthesis)

GGRO Grain growth rate (mg day^{-1} $grain^{-1}$ at optimum temperature)

GNUS 'Earring' or grain number per stem coefficient

DESV Vernalization sensitivity (% reduction in relative rate per missing vernalization day)

DESP Photoperiod sensitivity (% reduction in relative rate per h less than the threshold)

DUGF Grain-filling period (degree-days above 1 °C base)

As expected, it was found that the model simulations/predictions did not differ using the two different CERES versions. The advantage of the program is the time saved in creating a genetic file for the CERES-wheat model. Use of only the 1990 data to create the genetic file could be a mistake, since the wheat appears to not have grown under optimal water and nitrogen conditions throughout that season. This could be the reason for a cut-off point when simulating optimal conditions. For this reason the 1993 high water and nitrogen treatment from the physiology plots was also used to calculate the genotype coefficients. From these results it is clear that data from more than one year is really needed for the accurate determination of the genotype coefficients of an unknown cultivar. The genotype coefficients calculated by GENCALC for SST86 were used as the genetic input file for validating the CERES-wheat model.

10.2.5 CALIBRATION OF PUTU-WHEAT

A general genetic input file for PUTU 991 and 992 was set up by Singels & De Jager (1991a). In this article a table which contains all the values for the genetic input file for wheat can be found, except for the base photoperiod and vernalization values which change for different cultivars. The estimated photoperiod and vernalization sensitivity percentage values for cv. SST86, according to the Joubert table (Joubert, 1985), were obtained from the Grain Crops Institute (Small Grain Centre, Bethlehem). Joubert (1985) reported sensitivities to photoperiod and vernalization of 22 cultivars. These sensitivities were expressed as percentage of the sensitivity of a standard cultivar. Betta and SST101 were selected by Singels & de Jager (1991a), as the standard cultivars for photoperiod and vernalization respectively. Using these values, the base values for vernalization (V-BASE) and photoperiod (P-BASE) were calculated. The RMAX (maximum development rate) values were adapted for cv. SST86 for the phases of spikelet initiation and grain-filling, since a shorter duration from planting to anthesis and a longer duration for grain-filling were measured in the field (Table 10.5).

Table 10.5 Optimum (OPT) and base (BASE) values of temperature (T), photoperiod (P) and vernalization (V), and maximum rate of development (RMAX) for each phenological phase as set up by Singels & de Jager (1991a) for cv. SST86 under Roodeplaat conditions.

Parameter	Unit	Development phase					
		0	1	2	3	4	5
T-BASE	°C	0	0	2.8	5	8	8
T-OPT	°C	22	26	26	26	26	26
P-BASE	hour	-	-123.8*	-	-	-	-
P-OPT	hour	-	20	-	-	-	-
V-BASE	day	-	-1258*	-	-	-	-
V-OPT	day	-	50	-	-	-	-
Original RMAX	per d	0.250	0.086	0.050	0.150	0.200	0.067
Adapted RMAX	per d			0.055			0.045

*Is the value which needs to be changed for different cultivars.

Phase description:

0	Emergence
1	Leaf initiation
2	Spikelet initiation
3	Heading
4	Anthesis
5	Grain-filling

10.2.6 CALIBRATION OF SHOOTGRO

SHOOTGRO 4 was calibrated for spring wheat grown in South Africa using historic field datasets, in collaboration with Dr. G.S. McMaster during his visit in 1993 (see details in Chapter 4, section 4.5). Leaf length and Haun-index data from the 1992 field experiments at Roodeplaat were used to check the phyllochron intervals for three spring wheat cultivars grown at different levels of water and nitrogen stress. Roodeplaat 1990 data for kernels per spike and kernel position within the spike (de Kock, Walker & McDonald, 1991) was also used in the reproductive part of the model. Phenological data from the Cultivar Adaptation Trials conducted by the Small Grain Centre, were used for the calibration of the number of phyllochrons between anthesis and maturity (Kleingraansentrum, 1985).

10.3 Validation of Models

It is important for users of growth simulation models to know their accuracy. CERES-wheat version 2.10, PUTU-wheat versions 991 and 992 and SHOOTGRO version 4 were tested using the data collected over the four years of the project from the 25 different water and nitrogen treatments in each cv. SST86 experiment. Although additional cultivars were planted in 1992, the models could not be run for them as the yield component data were not measured, making it impossible to create the cultivar specific genetic files.

CERES 2.10, PUTU 991, PUTU 992 and SHOOTGRO 4 were run with the nitrogen subroutine switched off, i.e. ignoring nitrogen stress. The accuracy of the model simulations were tested against observed field data which included grain yield, water use, maximum LAI and anthesis date. CERES and SHOOTGRO were also run with the nitrogen balance included to test the nitrogen treatments. The simulated grain yield, yield components and biomass were tested against the observed field data.

The accuracy of the models was evaluated using a statistical program (spreadsheet) obtained from the University of the Orange Free State, Department of Agrometeorology, which calculates six different validation characteristics (de Jager, 1994). The statistical parameters used were:

S	slope through origin
r^2	coefficient of determination
D	index of agreement of Willmott (1981)
RMSE	root of the mean square error
MAE	mean absolute error expressed as a percentage of the mean of the measured values
D80	80% accuracy frequency

These are defined:

$$r^2 = \left[\sum_{n=1}^{n=N} (\hat{Y}n - \bar{\hat{Y}})\ (Yn - \bar{Y})^2\ /\ \sum_{n=1}^{n=N} (\hat{Y}n - \bar{\hat{Y}})\right]^2 (Yn - \bar{Y})^2 \qquad [10.1]$$

$$D = 1 - \sum_{n=1}^{n=N} (\hat{Y}n - Yn)^2\ /\ \sum_{n=1}^{n=N} |\hat{Y}n - \bar{Y}| + |Yn - \bar{Y}|^2 \qquad [10.2]$$

$$RMSE = \left[\sum_{n=1}^{n=N} (\bar{Y}n - Yn)^2\ /\ (N - 1)\right]^{0.5} \qquad [10.3]$$

$$MAE = 100 \sum_{n=1}^{n=N} |\hat{Y}n - Yn|\ /\ N\ \bar{Y} \qquad [10.4]$$

Where:

$\hat{Y}n$ *simulated data*

Yn *observed data*

$\bar{Y}$ *arithmetic mean of the measured data*

$\bar{\hat{Y}}$ *arithmetic mean of the simulated data*

The 80% statistic (D80) was computed as the percentage of simulated values agreeing within 20% of the measured values. According to de Jager (1994) it is generally accepted that models should perform within an accuracy of 20%. The criteria against which the statistics can be tested are listed in Table 10.7.

10.3.1 VALIDATION EXCLUDING THE NITROGEN BALANCE

The duration of growth from sowing to anthesis as simulated by the models is compared with measured data from the trial in Table 10.6.

Table 10.6 Actual duration (days) from sowing to anthesis for cv. SST86 in 1990-93, compared to the simulated duration by CERES, PUTU and SHOOTGRO.

MODEL	1990	1991	1992	1993
CERES 2.10	105	104	104	102
PUTU 992	100	102	105	99
SHOOTGRO 4	96 - 102	99 - 103	101 - 105	94 - 98
Actual data	90 - 97 (W1 - W5)	98 - 108 (W1 - W5)	98 - 105 (W1 - W5)	97 - 103 (W1 - W5)

The same phenological development periods were simulated by CERES and PUTU for the low and high water treatments. The experimental data showed a difference of between 6 and 10 days. SHOOTGRO managed to simulate this difference. The mean absolute errors between the measured and simulated duration of the period from sowing to anthesis for each models were:

CERES 4.60 days
PUTU 3.55 days
SHOOTGRO 3.10 days

These results for CERES compare very well with evaluations done by Otter-Nacke, Godwin & Ritchie (1986), who found a mean absolute error of 5 days for independent datasets and 7 days for dependent datasets. Singels & de Jager (1991a) tested PUTU 991 simulation ability for the duration of the period from sowing to anthesis over various datasets. They found a mean absolute error of 3 to 6 days, which compares favourably with this test of the model. Evaluations by French & Hodges (1985), Travis, Day & Porter (1988) and Maas & Arkin (1980) suggest that an accuracy of five days is highly acceptable.

Grain yield was well simulated for the high water treatments, except for CERES and SHOOTGRO where the yields were over- simulated during 1990. An under-simulation of yield by CERES and PUTU occurred at the low water treatments (Fig. 10.2; CERES D-value = 0.88; PUTU 991 D-value = 0.92; PUTU 992 D-value = 0.84; SHOOTGRO D-value = 0.84). From the statistical analysis one notices that PUTU 991 simulates the yield the most accurately (Table 10.7). Singels & de Jager (1991c) calculated a D-value of 0.91 when testing PUTU 991 with various datasets, which compares well with that calculated for PUTU 991 (D-value = 0.92) and PUTU 992 (D-value = 0.84). The D-value of 0.88 calculated for CERES is a bit better than a D-value of 0.81 calculated by Otter-Nacke & Ritchie (1985) when they tested CERES yield simulation using 245 different datasets.

Fig. 10.3 shows biomass simulated by CERES and SHOOTGRO plotted against measured data (CERES D-value = 0.80; SHOOTGRO = 0.78). (PUTU does not simulate biomass.) CERES under-simulated biomass at the low and high water treatments, while SHOOTGRO both over- and under-simulated the biomass at the high water treatments. The biomass simulation ability of CERES appears to be better than that of SHOOTGRO (Table 10.7).

Water consumption and the occasional drainage were simulated within the 20% fault lines by CERES and PUTU (SHOOTGRO uses the CERES water balance) for the low and medium water treatments (approximately 100 mm - 400 mm). An under-simulation of the water consumption occurred at the high water treatment (Fig. 10.4). PUTU 992 simulated the water consumption (including the drainage) better (D-value = 0.88) than PUTU 991 (D-value = 0.82). PUTU 991 simulated twice the amount of drainage at the higher water treatments than did PUTU 992. CERES (D-value = 0.88) and PUTU 992 simulated the water consumption quite acceptably (Table 10.7).

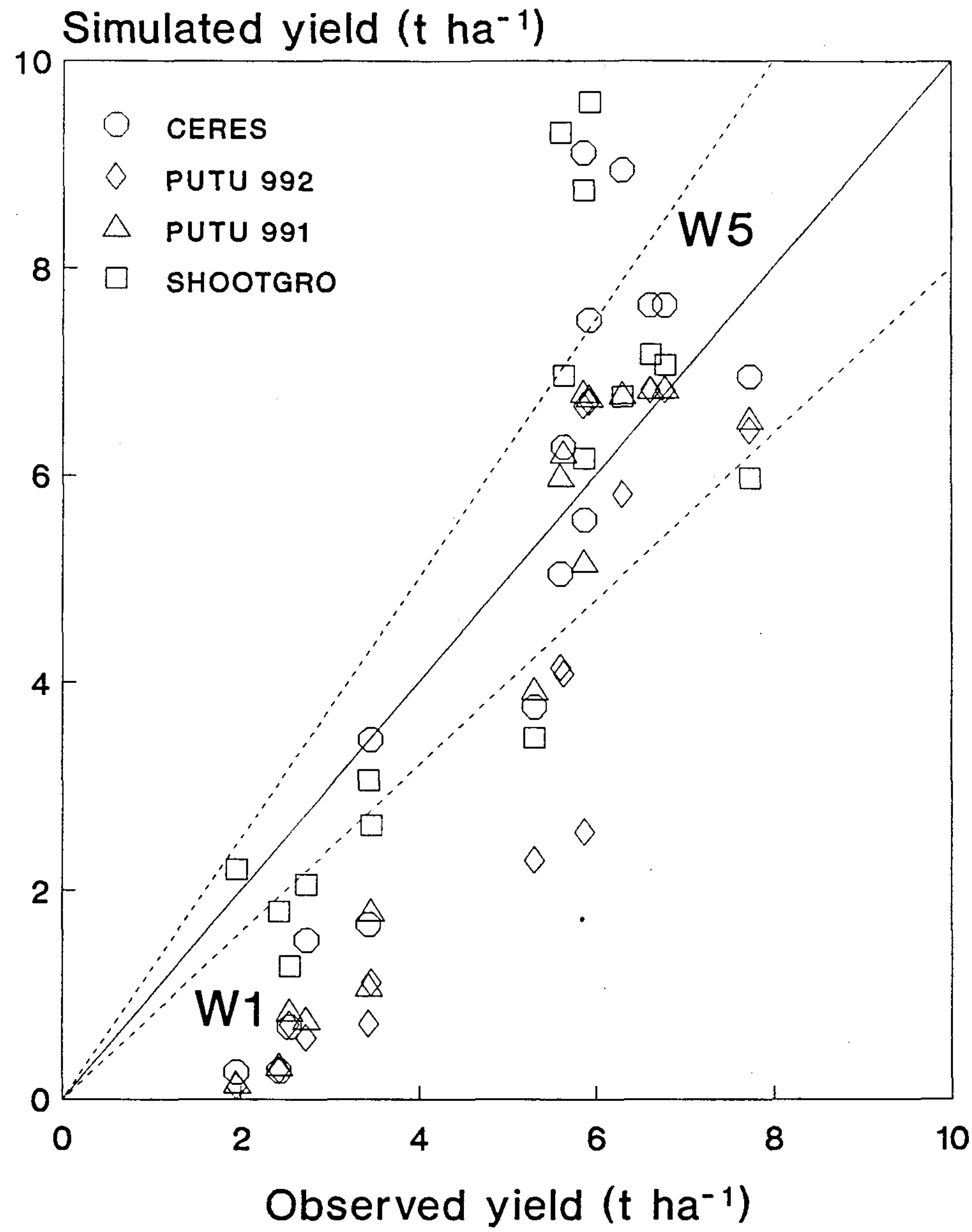


Fig. 10.2 Comparison of yield simulated by CERES 2.10, PUTU 991, 992 and SHOOTGRO 4 (excluding nitrogen balance) with the observed yield for cv. SST86 grown under increasing water treatments (W1-W5) at Roodeplaat in 1990-93.

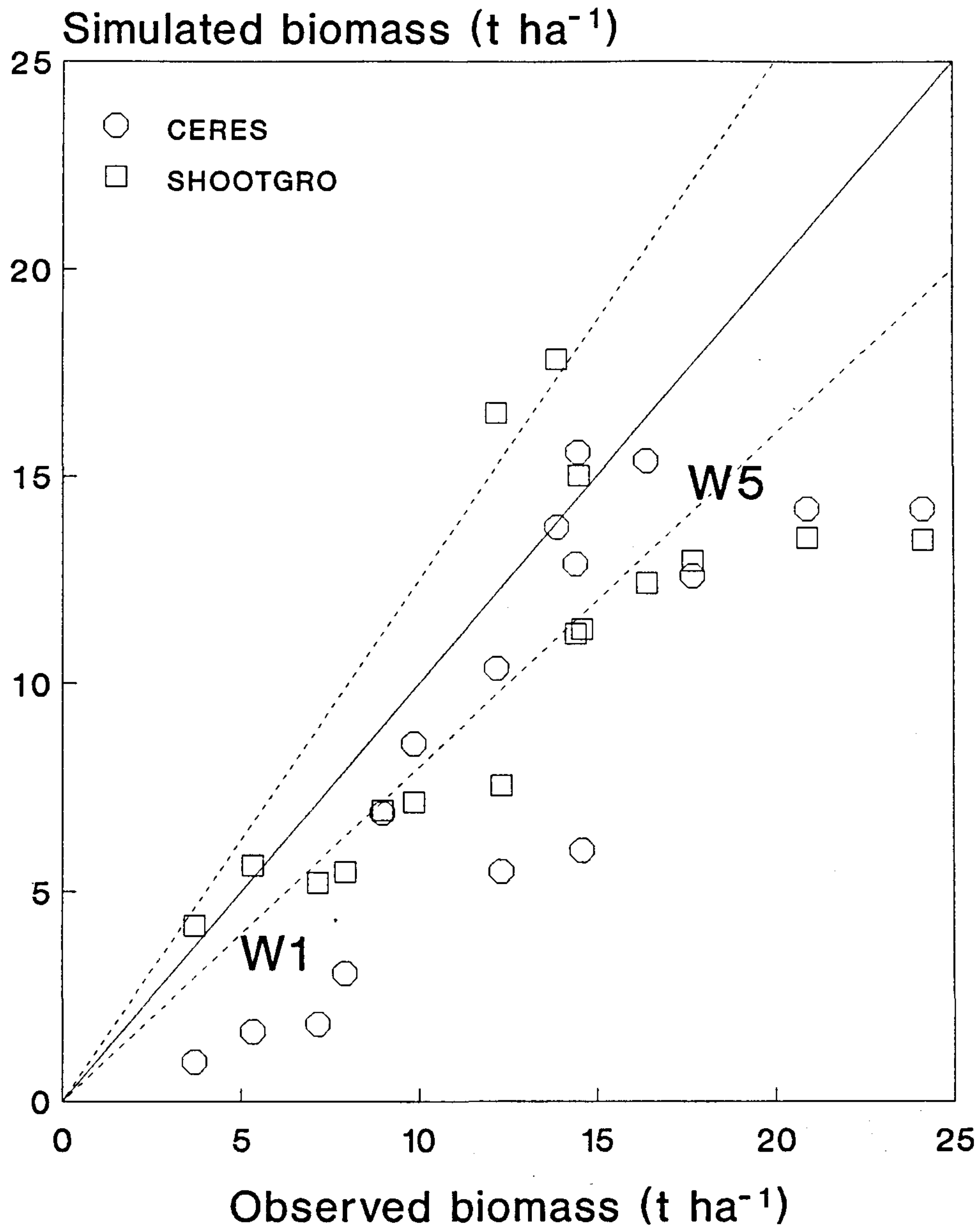


Fig. 10.3 Comparison of biomass simulated by CERES 2.10 and SHOOTGRO 4 (excluding nitrogen balance) with the observed biomass for cv. SST86 grown under increasing water treatments (W1-W5) at Roodeplaat in 1990-93.

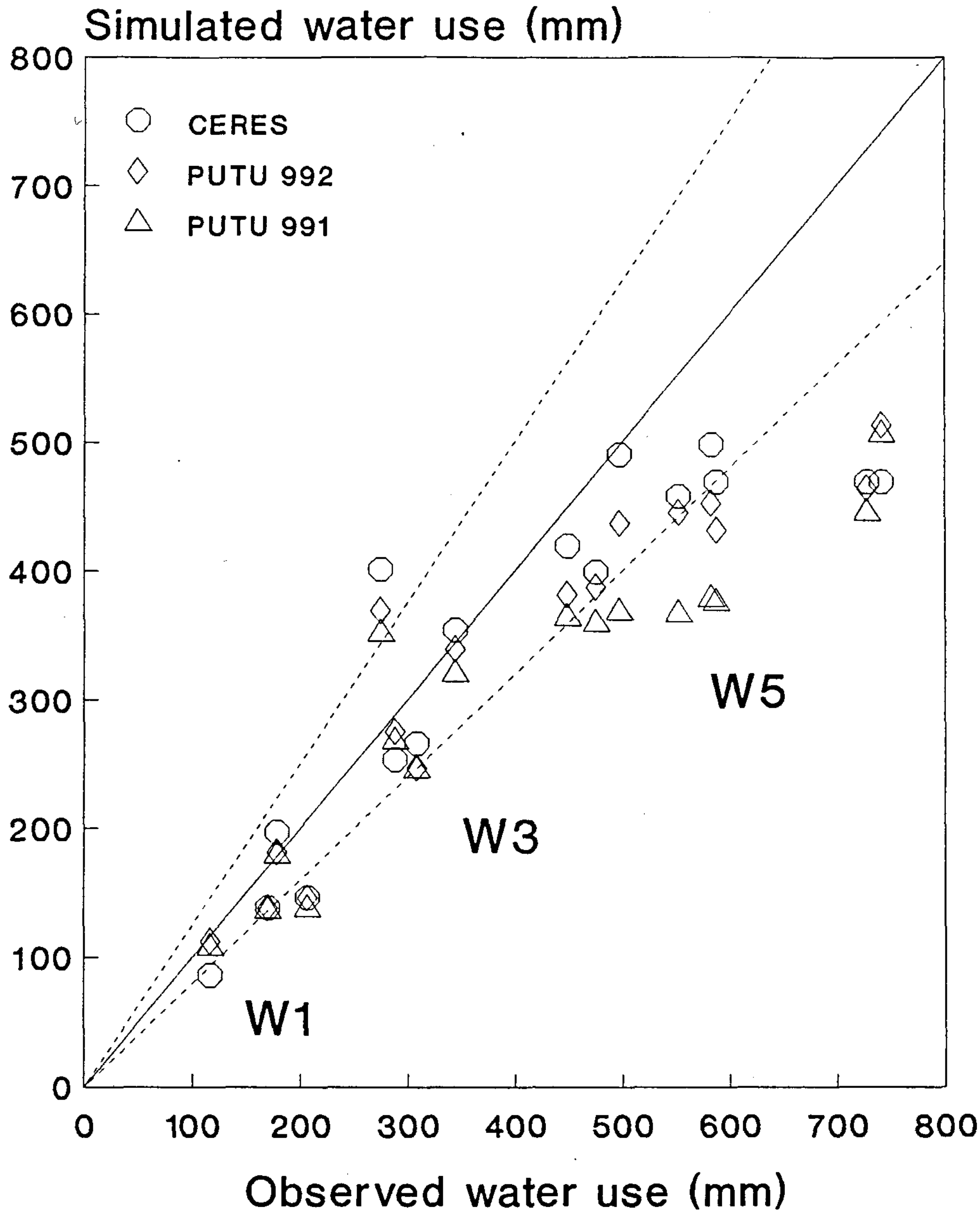


Fig. 10.4 Comparison of water use (including drainage) simulated by CERES 2.10, PUTU 991 and 992 (excluding nitrogen balance) with the observed water use for cv. SST86 grown under increasing water treatments (W1-W5) at Roodeplaat in 1990-93.

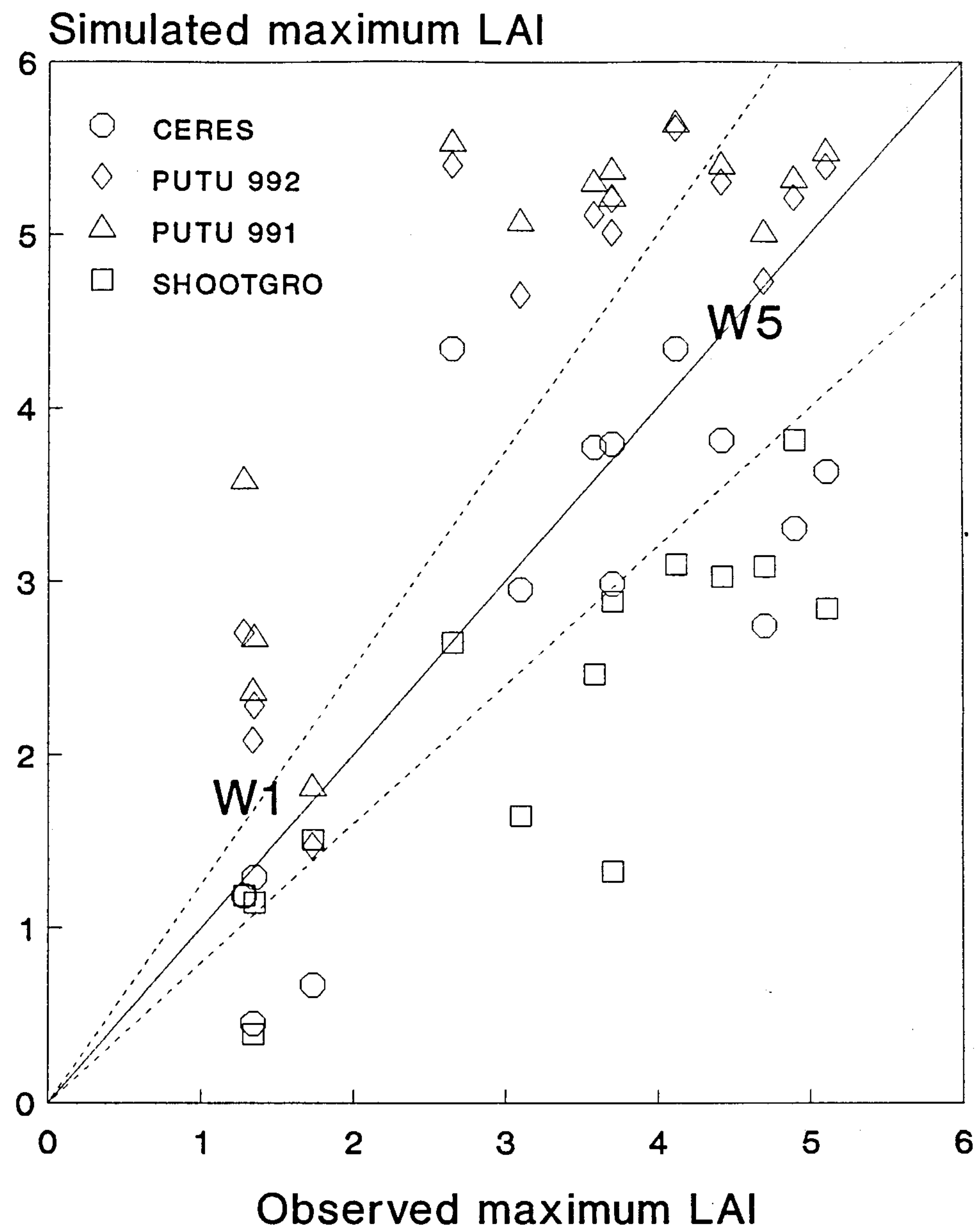


Fig. 10.5 Comparison of maximum leaf area index (LAI) simulated by CERES 2.10, PUTU 991, 992 and SHOOTGRO 4 (excluding nitrogen balance) with the observed maximum LAI for cv. SST86 grown under increasing water treatments (W1-W5) at Roodeplaat in 1990-93.

Table 10.7 Results of validation of CERES 2.10, PUTU 991 & 992 and SHOOTGRO 4 (excluding nitrogen balance) using wheat data collected at Roodeplaat in 1990-93.

Statistical parameters	CERES	PUTU 992	PUTU 991	SHOOTGRO	Reliability Criteria
YIELD					
S	1.04	0.79	0.92	1.10	0.9 - 1.1
r^2	0.83	0.83	0.92	0.66	> 0.8
D	0.88	0.84	0.91	0.84	> 0.8
MAE (%)	28	33	23	27	<20%
RMSE	1.60	1.88	1.35	1.73	
D80 (%)	44	38	56	38	>80%
N	16	16	16	16	
BIOMASS					
S	0.72			0.78	0.9 - 1.1
r^2	0.69			0.53	> 0.8
D	0.80			0.78	> 0.8
MAE (%)	31			28	<20%
RMSE	4.85			4.38	
D80 (%)	38			19	>80%
N	16			16	
WATER USE					
S	0.81	0.78	0.72		0.9 - 1.1
r^2	0.79	0.87	0.86		> 0.8
D	0.88	0.88	0.82		> 0.8
MAE (%)	20	21	27		<20%
RMSE	112.61	113.99	138.9		
D80 (%)	63	63	63		>80%
N	16	16	16		
MAXLAI					
S	0.84	1.26	1.31	0.67	0.9 - 1.1
r^2	0.58	0.72	0.67	0.72	> 0.8
D	0.85	0.81	0.73	0.76	> 0.8
MAE (%)	24	33	40	32	<20%
RMSE	1.01	1.28	1.51	1.27	
D80 (%)	57	36	29	29	>80%
N	14	14	14	14	

Table 10.7 shows that maximum leaf area index (MAXLAI) was most accurately simulated by CERES (D-value = 0.85). PUTU 991 and 992 both tended to over-simulate MAXLAI (D-values = 0.73 and 0.81 respectively), while CERES and SHOOTGRO (D-value = 0.76) tended to under-simulate it (Fig. 10.5). It is clear that the newer version of PUTU performed a lot better than the older version. Singels & de Jager (1991b) tested the MAXLAI simulation ability of PUTU 991 using various datasets, and calculated D-values from 0.360 to 0.923.

10.3.2 VALIDATION WITH THE NITROGEN BALANCE

The comparison between the simulated and measured duration of growth from sowing to anthesis was the same as that found when the models were validated excluding the nitrogen balance. Results of the statistical analysis for the model validation with the nitrogen balance included are presented in Table 10.8.

Yield was simulated slightly better by SHOOTGRO, with regard to the MAE (CERES = 42% and SHOOTGRO = 32%), although a D-value of 0.78 was calculated for both models. Figs 10.6(a) and 10.6(b) show the measured yield plotted against the yield simulated by CERES and SHOOTGRO respectively. There was an under-simulation by CERES at the low water treatments and an over-simulation at the high water, low nitrogen treatments. SHOOTGRO over-simulated yield at the middle to high water, low nitrogen treatments.

Biomass was under-simulated by CERES at the high and low water treatments (Fig. 10.7(a)), following the simulation tendency for yield. SHOOTGRO under-simulated at the high water, high nitrogen treatments and under-simulated at the high water, low nitrogen treatments (Fig. 10.7(b)). Biomass was simulated slightly better by CERES (D-value = 0.74) than SHOOTGRO (D-value = 0.71).

Kernel mass was simulated similarly for different water treatments by CERES, while the field data showed an significant increase in kernel mass with increase in water consumption (Fig. 10.8(a)). SHOOTGRO, however, simulated a larger difference in kernel mass over the different water treatments, compared to results from the field (Fig. 10.8(b)). Although the kernel mass was better simulated by CERES (D-value = 0.40) compared to SHOOTGRO (D-value = 0.10), it was still unacceptable.

Although analysis of the field data showed a significant increase in the number of kernels per ear as water and nitrogen increased, CERES and SHOOTGRO simulated a much greater difference (Fig. 10.9(a) and (b)). SHOOTGRO (D-value = 0.52) was able to simulate this yield component better than CERES (D-value = 0.41).

The number of ears per m^2 was simulated the most accurately out of the three yield components, with SHOOTGRO (D-value = 0.69) better than CERES (D-value = 0.53). For this yield component the year factor seems to play a role with the treatments and so explain the difference in simulated and observed data. CERES seems to simulate the difference in the number of ears per m^2 as water and nitrogen treatments changed, as was found in the field, except in 1991 when the yield components were greatly over-simulated for the W2 and low nitrogen treatments (Fig. 10.10(a)). During 1992 and 1993 the yield components were under-simulated at the middle to high water treatments. SHOOTGRO did not simulate a difference in number of ears per m^2 for different water and nitrogen treatments during 1992 (Fig. 10.10(b)).

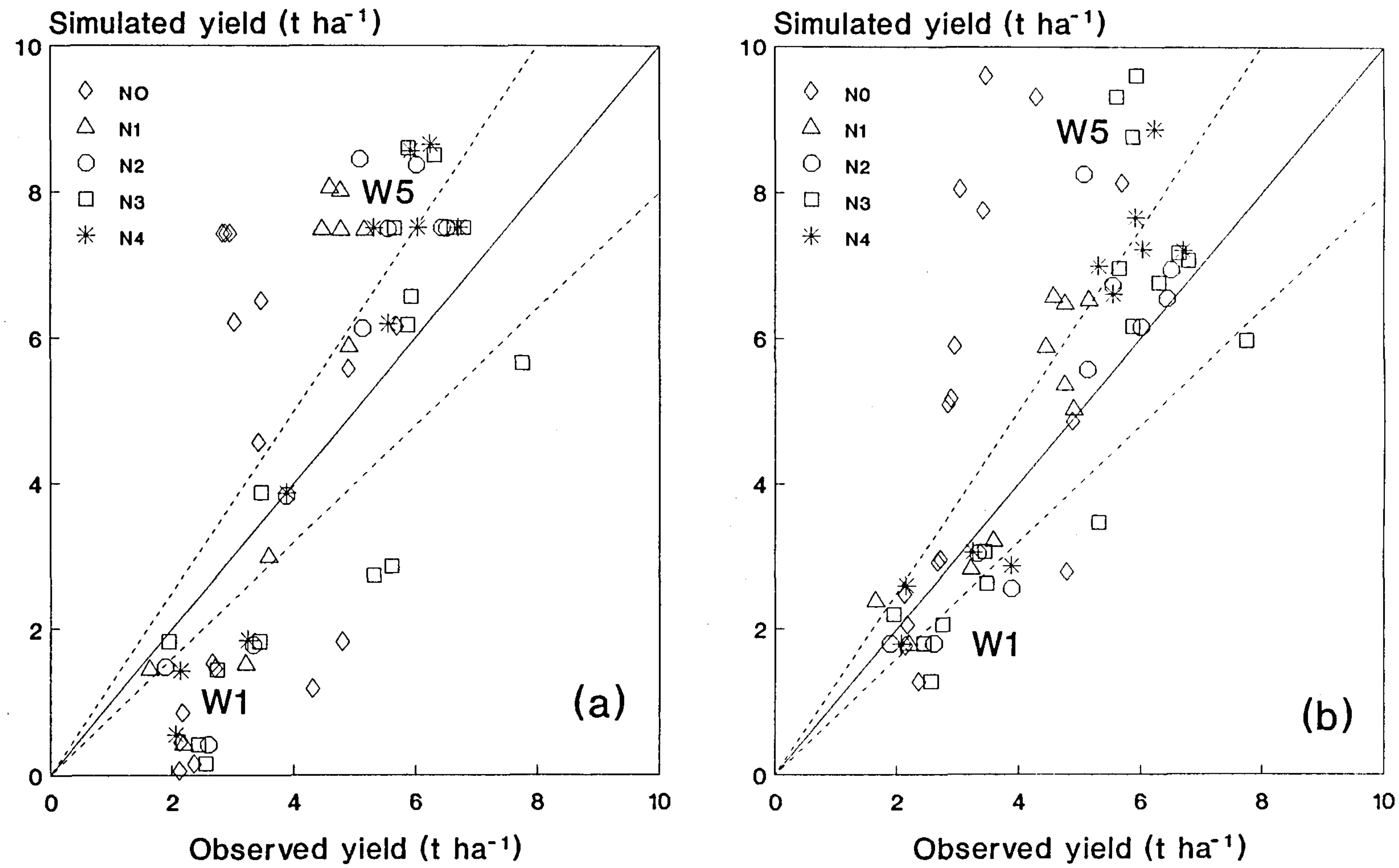


Fig. 10.6 Yield simulated by (a) CERES 2.10 and (b) SHOOTGRO 4 (including nitrogen balance) compared with the observed yield for cv. SST86 grown under increasing water and nitrogen treatments (W1-W5, N0-N4) at Roodeplaat in 1990-93.

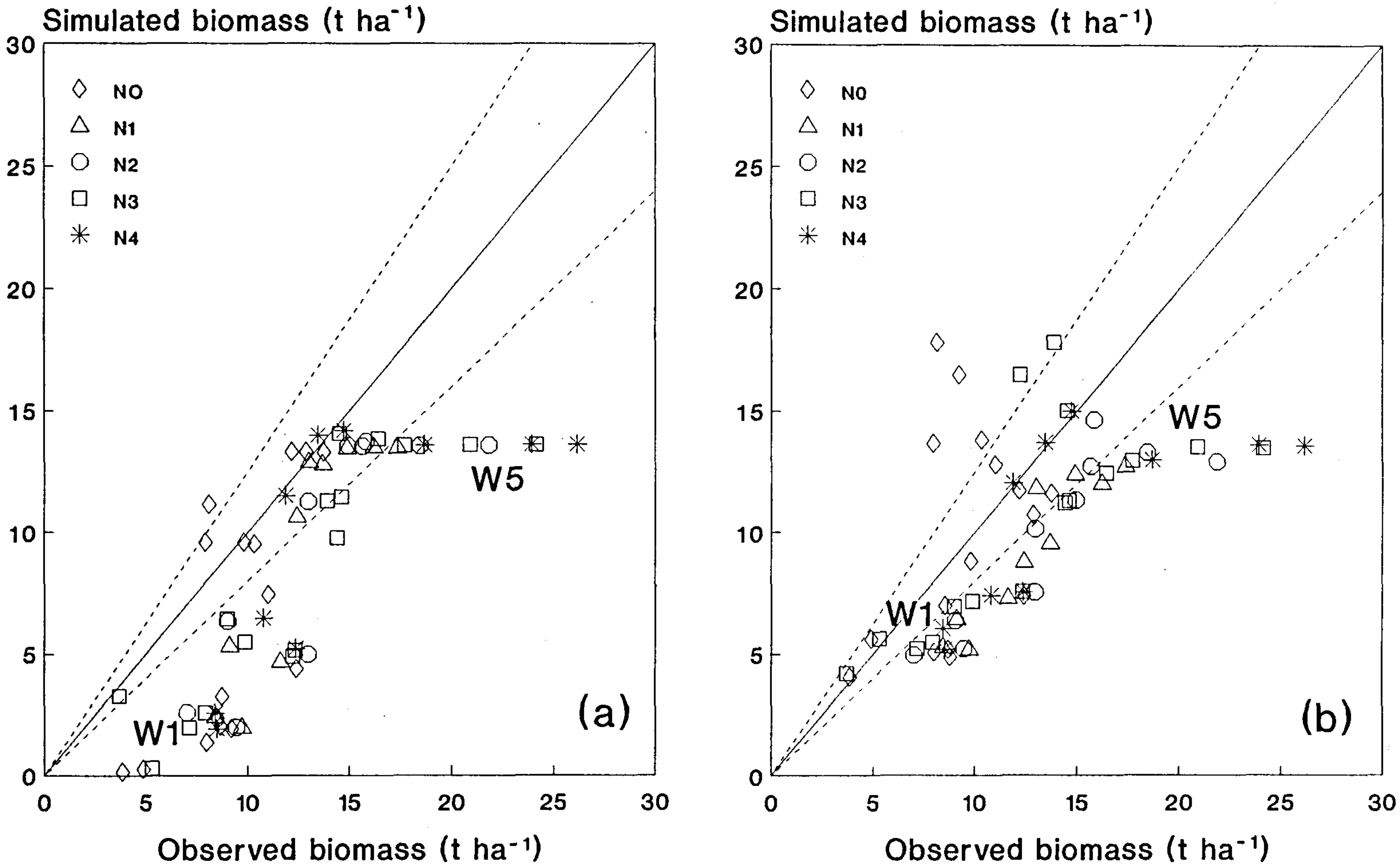


Fig. 10.7 Biomass simulated by (a) CERES 2.10 and (b) SHOOTGRO 4 (including nitrogen balance) compared with the observed biomass for cv. SST86 grown under increasing water and nitrogen treatments (W1-W5, N0-N4) at Roodeplaat in 1990-93.

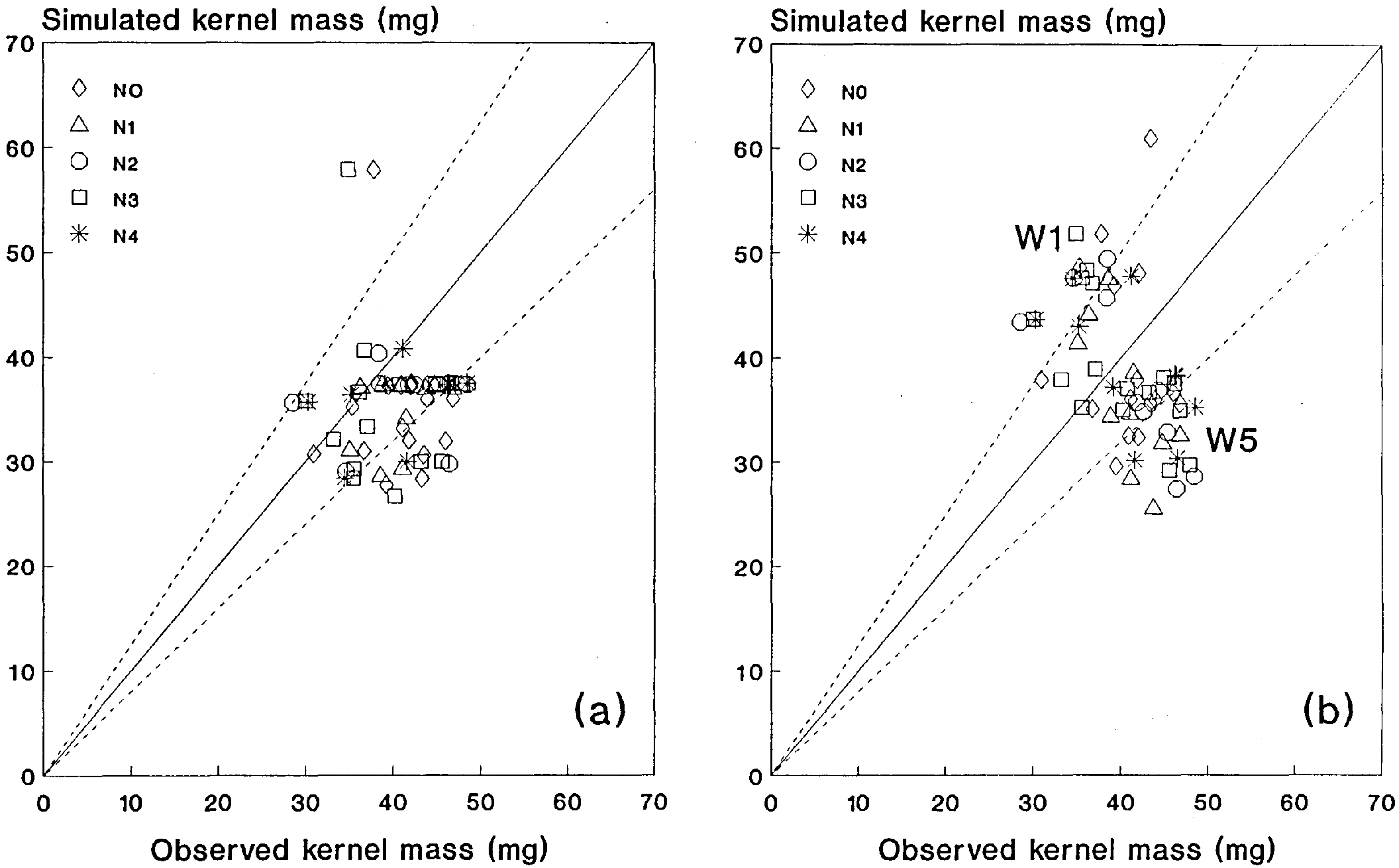


Fig. 10.8 Kernel mass simulated by (a) CERES 2.10 and (b) SHOOTGRO 4 (including nitrogen balance) compared with the observed kernel mass for cv. SST86 grown under increasing water and nitrogen treatments (W1-W5, N0-N4) at Roodeplaat in 1990-93.

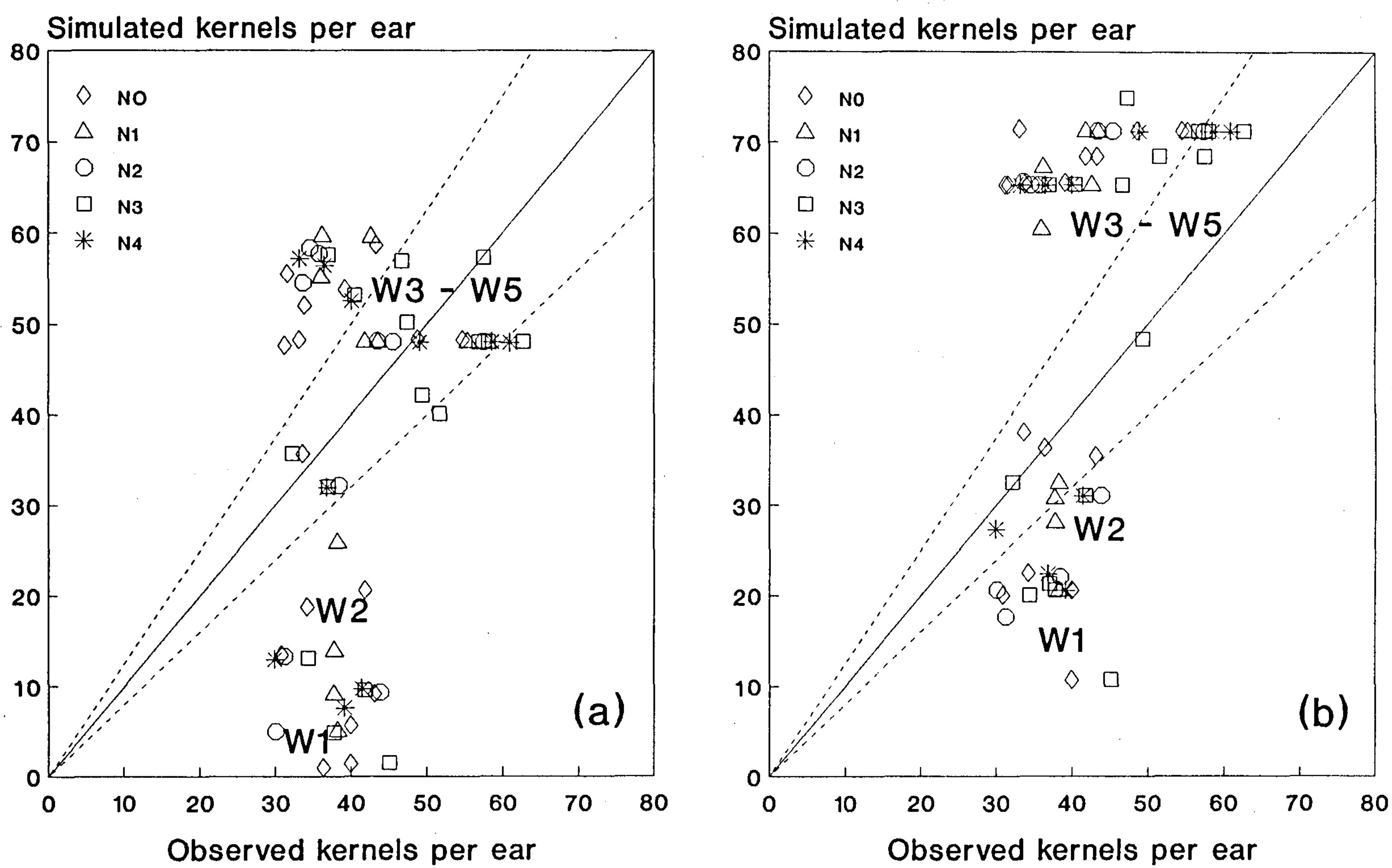


Fig. 10.9 Number of kernels per ear simulated by (a) CERES 2.10 and (b) SHOOTGRO 4 (including nitrogen balance) compared with the observed number for cv. SST86 grown under increasing water and nitrogen treatments (W1-W5, N0-N4) at Roodeplaat in 1990-93.

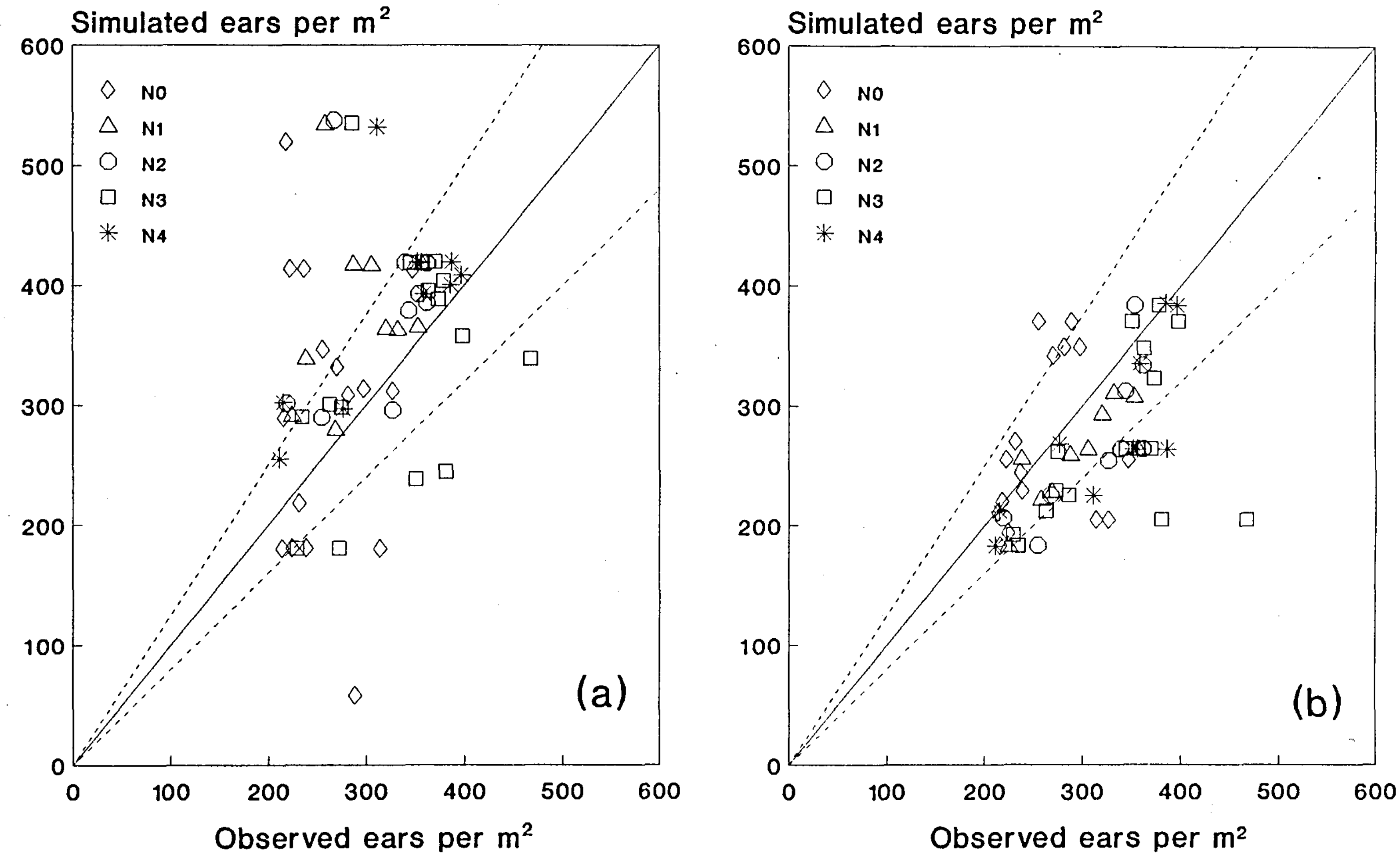


Fig. 10.10 Number of ears per m^2 simulated by (a) CERES 2.10 and (b) SHOOTGRO 4 (including nitrogen balance) compared with the observed number for cv. SST86 grown under increasing water and nitrogen treatments (W1-W5, N0-N4) at Roodeplaat in 1990-93.

Table 10.8 Results of validation of CERES 2.10 and SHOOTGRO 4 (including nitrogen balance) using wheat data collected at Roodeplaat in 1990-93.

Statistical parameters	CERES	SHOOTGRO	Statistical parameters	CERES	SHOOTGRO
YIELD			KERNEL MASS		
S	1.13	1.19	S	0.86	0.93
r^2	0.56	0.53	r^2	0.01	0.26
D	0.78	0.78	D	0.40	0.1
MAE (%)	42	32	MAE (%)	18	24
RMSE	2.12	1.92	RMSE	8.89	10.74
D80 (%)	27	45	D80 (%)	66	44
N	62	62	N	62	62
BIOMASS			KERNELS PER EAR		
S	0.69	0.77	S	0.86	1.22
r^2	0.61	0.39	r^2	0.10	0.22
D	0.74	0.71	D	0.41	0.52
MAE (%)	34	29	MAE (%)	41	46
RMSE	5.16	4.49	RMSE	20.15	21.32
D80 (%)	34	29	D80 (%)	32	18
N	62	62	N	62	62
EARS PER m^2					
S	1.12	0.86			
r^2	0.11	0.26			
D	0.53	0.69			
MAE (%)	26	18			
RMSE	105.955	71.10			
D80 (%)	62	61			
N		62			

10.3.3 PROPOSED ADAPTATIONS

From the validation it was clear that the biomass was under simulated by the models at the low water treatments (dryland conditions). As one of the places for a potential error in the simulation of biomass by the model is the relationship between intercepted PAR and total

PAR, this was investigated. In CERES this was done by checking the radiation interception equation using the measured leaf area index and radiation data from a single year (1993).

$$\frac{IPAR}{PAR} = 1 - EXP^{(-0.85 \times LAI)} \qquad [10.5]$$

where:

IPAR	fraction of radiation intercepted by the crop
PAR	photosynthetically active radiation
LAI	leaf area index
-0.85	extinction coefficient

The procedure followed was to use the measured radiation interception data for wheat cv. SST86 to calculate the extinction coefficient at Roodeplaat. GENSTAT was used to fit the measured data to a non-linear equation. An extinction coefficient of -0.9821 was calculated with 60.1 % of the variance accounted for. Fig. 10.11 shows the data and the equation presently used in the model. It seems that the extinction coefficient currently used is probably too high and -0.98 would probably be a better value. This can potentially provide a solution to the problem of the low biomass simulation under dryland conditions. A sensitivity analysis using a range of values for the extinction coefficient of 0.65 to 0.95 indicated that the accuracy of the coefficient was not a critical factor in determinating IPAR unless LAI values of less than 1.5 persisted throughout the season (Ritchie, 1991). This is the case for dryland conditions. Thus for optimal use of CERES-wheat in South Africa it would be advisable to have the extinction coefficient as an input rather than a set value as at present.

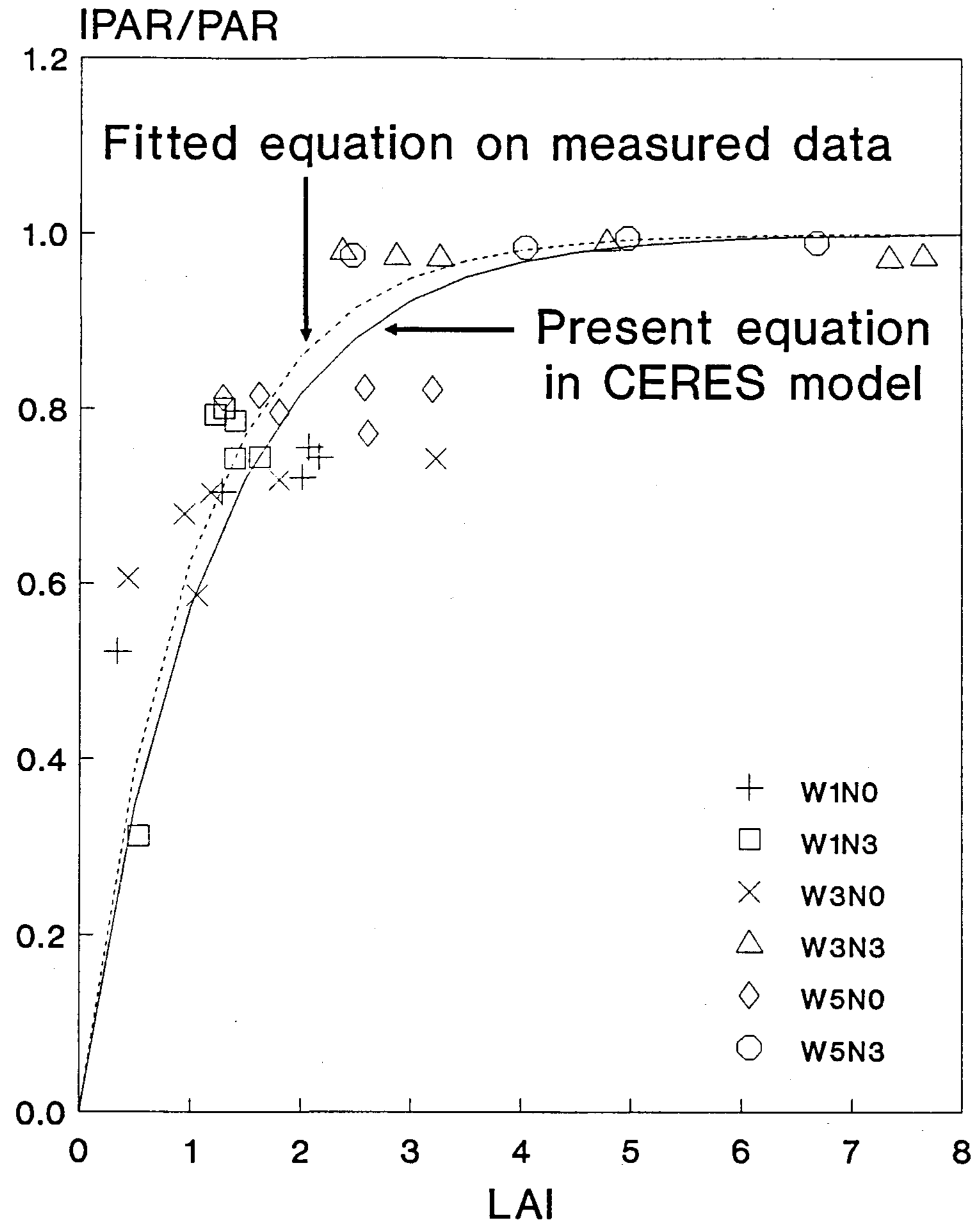


Fig. 10.11 The relationship between IPAR/PAR and LAI for cv. SST86 grown under increasing water and nitrogen treatments (W1-W5, N0-N3) at Roodeplaat in 1993. A comparison is made of the radiation interception equation fitted on measured data and the equation presently used in CERES 2.10.

10.4 Conclusion

The calibration and validation of the CERES, PUTU and SHOOTGRO wheat crop models for local cultivars and conditions is a major undertaking, but considerable progress has been made with regard to that objective in this project. The soil parameters in the models have received adequate attention, but further work is still necessary to test other sections, such as the plant parameters, under local conditions. The experimental dataset obtained in this project will be of great benefit to developers and other scientists in the improvement of crop simulation models.

Chapter 11

CONCLUSIONS AND RECOMMENDATIONS

The objectives of this study centred around the interactive effects of water and nitrogen on the growth, water use and yield of irrigated spring wheat. A comprehensive series of field measurements was made, and the information was then used to validate various crop models.

(i) The characterization of crop canopy development was undertaken in great detail in all four wheat seasons by means of growth (e.g. leaf area and biomass) and physiological (e.g. photosynthesis) measurements. A detailed study of the often neglected crop root system was also made, with the help of a minirhizotron video camera system. Plant water relations were monitored by means of leaf water potential measurements, and the rate of sap flow through a single stem was successfully measured after adapting and calibrating the heat pulse method.

(ii) Selected crop growth models in current use were calibrated and validated under South African conditions using the comprehensive dataset generated in the field experiments.

(iii) The BEWAB irrigation program was used to schedule the irrigation throughout the four year project, and proved its reliability when tested against measured yield and water use data.

11.1 Crop Growth and Development

The growth and development of four wheat crops has been thoroughly measured and documented during this project. A large amount of leaf area and biomass data has been diligently collected from a range of water-nitrogen treatments. This dataset will be most valuable in future for the further improvement, development and adaptation of crop growth models, particularly as the water content of the soil and the water status of the leaves were also measured with great precision. The value of the dataset is further enhanced by the fact that five water treatments were monitored each year, some of which represent deficit irrigation conditions which are widely practised in South Africa.

Progress with root measurements using the minirhizotron system was satisfactory. This technique is new in South Africa and has now been tested against conventional root measurements from soil core samples. Although the technique will not replace the traditional methods for root sampling in the field, it does have many distinct advantages. It also provides the potential to collect much valuable data of a qualitative nature on the effects of various water and other treatments on the growth and morphology of roots. The technique is ideally suited to perennial plants where root turnover can be monitored over long periods.

* It is recommended that the minirhizotron system be used, for example, to monitor the effects of environmental stress, particularly drought, fire or elevated CO_2 on the growth of natural grasses and shrubs in a savanna ecosystem with a view to developing a better understanding of the production potential of the natural veld in South Africa under a limited water supply.

* The expertise developed during this project can provide a useful service to the scientific community in South Africa, as very few studies include root measurements.

* Further work is needed to develop a computerized interpretation method to speed up the process of translating root video images into quantitative data.

11.2 Leaf Photosynthesis

To further characterize the growth of the crop, detailed measurements of the capacity of the leaf factory in terms of photosynthesis rate were needed. Guidelines were developed for the precautionary measures needed during the use of leaf chambers to measure single leaf photosynthesis in the field. Measurements of a consistently high quality can be made successfully on a routine basis if these precautions are followed. The pattern of wheat leaf photosynthesis is dependent on leaf age and these changes were monitored under a range of water and nitrogen availabilities in the field to characterize the effects of water stress.

* The use of the photosynthesis apparatus for monitoring the water and nitrogen status of plants on a routine basis needs to be developed, with a view to providing a trouble-shooting service.

* There is a need to investigate the use of the technique to monitor the growth and production patterns of various crops and the effect of different conditioning treatments (such as mild or severe water stress at critical periods) on plant physiology.

* Photosynthesis of vegetable crops needs to be investigated as there is little data available, particularly under conditions of water stress and deficit irrigation.

The findings concerning the dependence of leaf photosynthesis on the age of wheat leaves will lead to a better understanding of the contribution of each leaf, and the relationship with canopy level photosynthesis and its contribution to overall crop production. This information can be used to improve carbon partitioning and photosynthesis models. The relationships between photosynthesis and leaf nitrogen can be used as indicators for the decisions concerning mid-season fertilizer top-dressings.

11.3 Water Flow Through the Plant

It was of specific interest in this project to look at the water flow at different levels in the soil-plant-atmosphere system. The evapotranspiration has often been considered in similar studies, but in this instance the sap flow through individual plants was measured so that water flow at different levels in the biological system could be compared under the various irrigation regimes. The adaptation of the heat pulse system to measure transpiration of a single wheat tiller was a great success. This technique is highly complicated and requires the operation of sophisticated equipment, so it is only recommended for use by highly skilled and dedicated scientists with a specific need to measure plant transpiration. The method can been used in many different situations, including woody, herbaceous and annual plants.

* The heat pulse technique can be extended to measure the transpiration of indigenous species and hence help to elucidate the water relations in these habitats.

* It also has the potential for use in evapotranspiration studies where there is a need to partition the soil and plant components of evaporation. This could be further investigated as part of other existing projects.

* The study of the effects of water stress on the resistances to water flow through the soil-plant-atmosphere continuum has only scratched the surface, and so this detailed work needs to be pursued. If the location of high resistance to water flow could be identified, it would be a step towards increasing the efficiency of water transport through the system, which could potentially increase the water use efficiency of crops. This type of highly theoretical study should be maintained.

11.4 Crop Simulation Models

The calibration and validation of crop models for local cultivars and conditions is no small task. The calibration of the wheat models, CERES, PUTU and SHOOTGRO, has been done to the best of our ability with the current data available. The soil parameters have received adequate attention and progress has been made with the soil water balance sub-models. However, much effort is still needed as there are still many sections of the models that have yet to be tested against locally-collected datasets.

* The plant parameters within the models have received little attention and need further validation for South African varieties and conditions. If a single portion of the model is refined to such a degree that the other sub-models are at a lower level of accuracy, the output of the model as a whole will be limited by the least accurate sub-model.

* The crop aspects such as partitioning of biomass between roots and tops, maximum photosynthesis rates and the calculation of harvest indices still need to be tested

against the locally-collected data now available as a result of this project.

As the potential use of a well calibrated and tested crop simulation model covers a broad spectrum of the agricultural community, it is well worth the enormous effort of many researchers presently involved in the field. However, the research must be focussed on the areas of the models which perform worst at present and which are most sensitive to changes.

11.5 BEWAB Irrigation Program

The BEWAB scheduling program was used to plan the irrigation for the wheat experiments. Soil water content was monitored throughout the season and the crop water use and final grain yield data were then used to test the reliability of the program. Although BEWAB was developed in the cooler Orange Free State region, it performed quite well with spring wheat at Roodeplaat. If it is to be used regularly in the warm irrigation region in South Africa then certain modifications could now be made with the help of the information gained in this project.

* Data recorded during this study could contribute towards the verification of the driving force equations used in BEWAB. Particular reference is made to the root and soil water dataset collected over the four years under different environmental conditions to those used for the original program. As this dataset is from a different region to that used in the development of the program, it could potentially help to broaden the application base for BEWAB.

The comprehensive study of the effects of a range of water and nitrogen application levels on spring wheat enabled guidelines to be developed regarding the amount of irrigation water to apply and the optimal nitrogen application recommended for a specific target yield. This information could be of great value to farmers in the warm irrigation region.

11.6 General Conclusion

This project can be considered a success, despite initial setbacks due to lack of manpower, and the objectives were for the most part achieved.

The evaluation, adaptation and improvement of the highly specialized techniques to monitor root growth using a minirhizotron video camera system and to measure single stem transpiration using the heat pulse method were successful. In addition, the development of guidelines and clarification of the precautions needed when using a single leaf photosynthesis chamber have contributed to the collection of reliable photosynthesis data.

Although the crop models were not tested at farm level, a valuable contribution has been made to their calibration and validation for South African irrigated spring wheat.

Given the time and opportunity there is much more that could done with the vast amount of information collected during this project, relating to both wheat and soybean crops. The datasets will therefore be made available to any scientist who is able to make further use of them. In this way it is felt that the study has contributed to the furtherance of agricultural science in South Africa at the present time, and that the effect of the scientific progress will be realised in the years to come.

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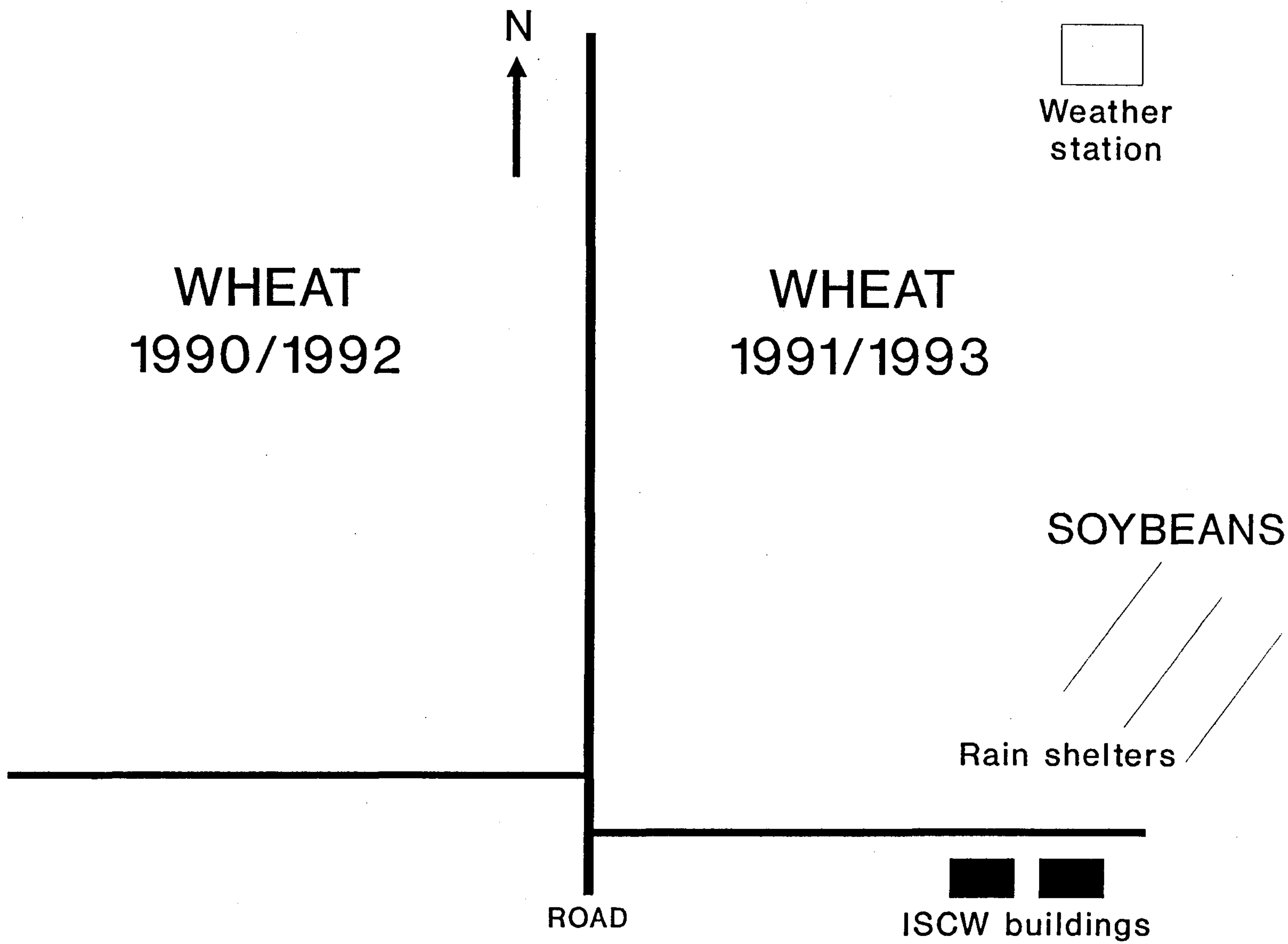


Plan of ISCW Roodeplaat Experimental Station

Wheat 1990 Linesource

2-weekly frequency

N3 1	N2 2	N4 3	N0 4	N4 5
N0 10	N0 9	N2 8	N4 7	N0 6
N1 11	N1 12	N3 13	N2 14	N2 15
N2 20	N4 19	N0 18	N1 17	N3 16
N4 21	N3 22	N1 23	N3 24	N1 25

W1	W2	W3	W4	W5
N3 75	N0 74	N1 73	N2 72	N2 71
N2 66	N1 67	N0 68	N0 69	N3 70
N0 65	N2 64	N2 63	N4 62	N0 61
N4 56	N3 57	N4 58	N1 59	N1 60
N1 55	N4 54	N3 53	N3 52	N4 51
W1	W2	W3	W4	W5

Side 1

W5	W4	W3	W2	W1
N2 30	N2 29	N4 28	N3 27	N3 26
N3 31	N4 32	N1 33	N1 34	N4 35
N4 40	N1 39	N2 38	N0 37	N2 36
N1 41	N3 42	N0 43	N4 44	N0 45
N0 50	N0 49	N3 48	N2 47	N1 46
W5	W4	W3	W2	W1

Side 2

LINESOURCE

Weekly frequency

N0 80	N2 79	N1 78	N3 77	N3 76
N4 81	N3 82	N4 83	N 84	N1 85
N3 90	N4 89	N2 88	N 87	N0 86
N1 91	N0 92	N3 93	N1 94	N4 95
N2 100	N1 99	N0 98	N4 97	N2 96

W1	W2	W3	W4	W5
N0 101	N4 102	N0 103	N3 104	N3 105
N2 110	N2 109	N3 108	N1 107	N2 106
N1 111	N1 112	N2 113	N2 114	N0 115
N3 120	N3 119	N1 118	N4 117	N1 116
N4 121	N0 122	N4 123	N0 124	N4 125
W1	W2	W3	W4	W5

Side 1

W5	W4	W3	W2	W1
N0 146	N2 147	N0 148	N3 149	N2 150
N4 145	N0 144	N2 143	N4 142	N0 141
N1 136	N4 137	N1 138	N1 139	N4 140
N2 135	N1 134	N3 133	N0 132	N1 131
N3 126	N3 127	N4 128	N2 129	N3 130
W5	W4	W3	W2	W1

Side 2

LINESOURCE

Wheat 1991 Linesource

2-WEEKLY FREQUENCY

Side 1

W1	N1 5	N4 6	N0 15	N2 16	N3 25
W2	N4 4	N3 7	N2 14	N1 17	N0 24
W3	N3 3	N4 8	N2 13	N0 18	N1 23
W4	N3 2	N1 9	N4 12	N0 19	N2 22
W5	N4 1	N1 10	N0 11	N3 20	N2 21

W1	N2 26	N0 35	N3 36	N4 45	N1 46
W2	N1 27	N0 34	N3 37	N2 44	N4 47
W3	N2 28	N0 33	N4 38	N3 43	N1 48
W4	N0 29	N4 32	N3 39	N1 42	N2 49
W5	N1 30	N4 31	N2 40	N3 41	N0 50

LINESOURCE

Side 2

W5	N0 100	N1 91	N4 90	N3 81	N2 80
W4	N0 99	N3 92	N1 89	N4 82	N2 79
W3	N3 98	N0 93	N2 88	N1 83	N4 78
W2	N2 97	N4 94	N0 87	N1 84	N3 77
W1	N1 96	N0 95	N2 86	N4 85	N3 76

W5	N4 71	N2 70	N1 61	N0 60	N3 51
W4	N3 72	N4 69	N1 62	N0 59	N2 52
W3	N1 73	N0 68	N3 63	N2 58	N4 53
W2	N3 74	N1 67	N2 64	N4 57	N0 54
W1	N1 75	N3 66	N2 65	N0 56	N4 55

WEEKLY FREQUENCY

Side 1

W1	N4 105	N3 106	N1 115	N2 116	N0 125
W2	N0 104	N3 107	N1 114	N2 117	N4 124
W3	N4 103	N1 108	N2 113	N3 118	N0 123
W4	N0 102	N4 109	N2 112	N1 119	N3 122
W5	N4 101	N1 110	N0 111	N2 120	N3 121

W1	N2 126	N1 135	N3 136	N4 145	N0 146
W2	N1 127	N0 134	N4 137	N3 144	N2 147
W3	N0 128	N3 133	N2 138	N4 143	N1 148
W4	N4 129	N1 132	N2 139	N0 142	N3 149
W5	N2 130	N4 131	N0 140	N1 141	N3 150

LINESOURCE

Side 2

W5	N3 200	N2 191	N1 190	N4 181	N0 180
W4	N3 199	N1 192	N4 189	N0 182	N2 179
W3	N4 198	N3 193	N1 188	N2 183	N0 178
W2	N2 197	N0 194	N1 187	N4 184	N3 177
W1	N3 196	N1 195	N4 186	N0 185	N2 176

W5	N2 171	N3 170	N1 161	N0 160	N4 151
W4	N1 172	N3 169	N2 162	N0 159	N4 152
W3	N1 173	N2 168	N4 163	N0 158	N3 153
W2	N1 174	N0 167	N2 164	N4 157	N3 154
W1	N4 175	N1 166	N0 165	N3 156	N2 155

Wheat 1992 & 1993 Linesource

Side 1

W1	N4 5	N3 6	N1 15	N2 16	N0 25	N2 26	N1 35	N3 36	N4 45	N0 46	W1
W2	N0 4	N1 7	N3 14	N2 17	N4 24	N1 27	N0 34	N4 37	N3 44	N2 47	W2
W3	N4 3	N1 8	N2 13	N3 18	N0 23	N0 28	N3 33	N2 38	N4 43	N1 48	W3
W4	N0 2	N4 9	N2 12	N1 19	N3 22	N4 29	N1 32	N2 39	N0 42	N3 49	W4
W5	N4 1	N1 10	N0 11	N2 20	N3 21	N2 30	N4 31	N0 40	N1 41	N3 50	W5

LINESOURCE

Side 2

W5	N3 100	N2 91	N1 90	N4 81	N0 80	N2 71	N3 70	N1 61	N0 60	N4 51	W5
W4	N3 99	N1 92	N4 89	N0 82	N2 79	N1 72	N3 69	N2 62	N0 59	N4 52	W4
W3	N4 98	N3 93	N1 88	N2 83	N0 78	N1 73	N2 68	N4 63	N0 58	N3 53	W3
W2	N2 97	N0 94	N1 87	N4 84	N3 77	N1 74	N0 67	N2 64	N4 57	N3 54	W2
W1	N0 96	N3 95	N1 86	N4 85	N2 76	N1 75	N4 66	N0 65	N3 56	N2 55	W1

Wheat 1991 Physiology Plots

REP 1	REP 2	REP 3
201 W1N0	212 W3N3	213 W1N3
202 W5N0	211 W3N0	214 W1N0
203 W3N3	210 W5NO	215 W3N3
204 W3N0	209 W1N3	216 W5N0
205 W5N3	208 W5N3	217 W5N3
206 W1N3	207 W1N0	218 W3N0

Wheat 1992 Physiology Plots

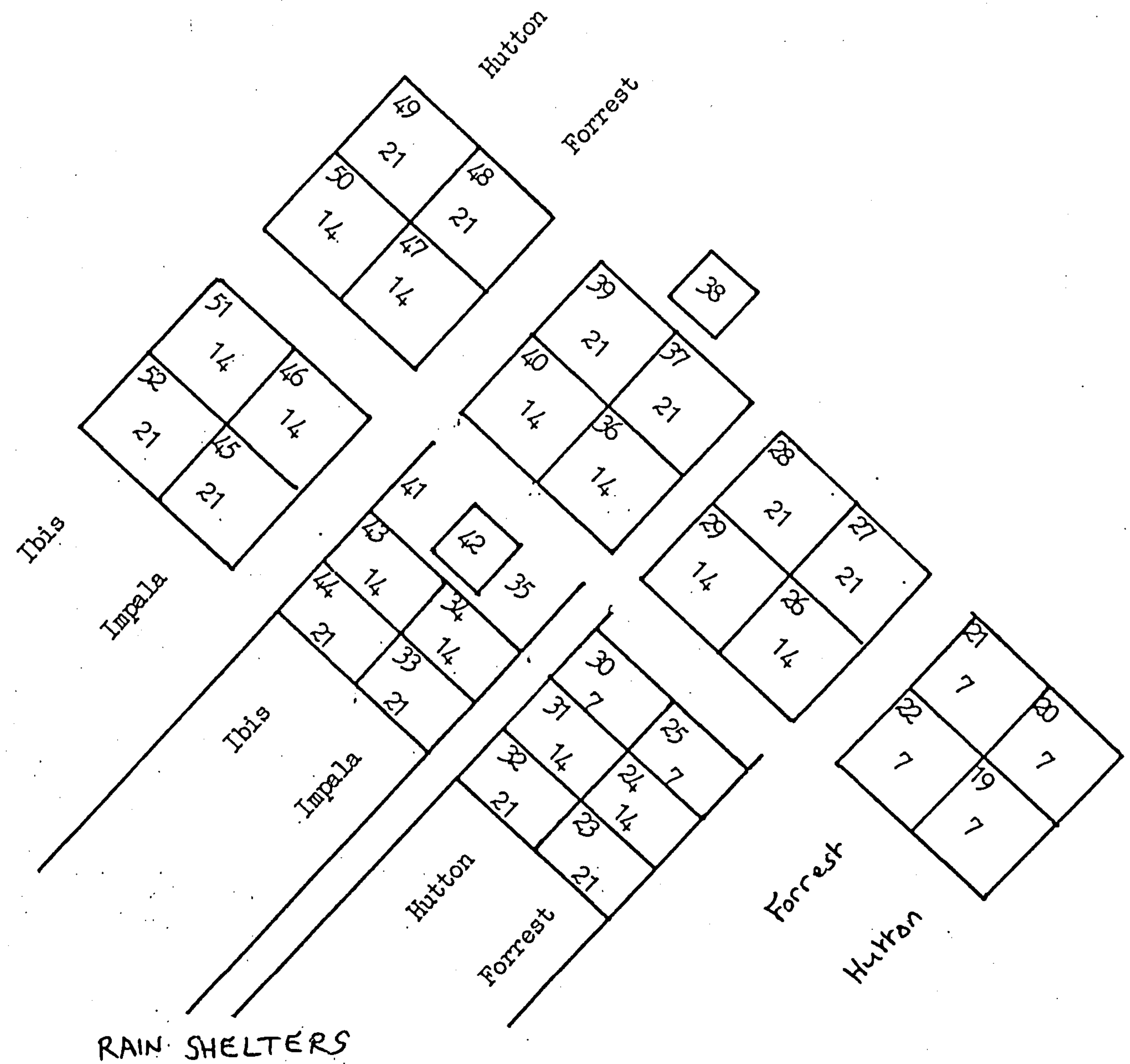
101	W3N0	120	W1N3	
102	W5N0	119	W1NO	REP 1
103	W5N3	118	W3N3	
104	W3N0	117	W1N3	
105	W5NO	116	W5N3	REP 2
106	W3N3	115	W1NO	
107	W1N3	114	W5N3	
108	W3N0	113	W3N3	REP 3
109	W1N0	112	W5NO	
110	W5AN3	111	W5AN3	

Wheat 1993 Physiology Plots

122 W1N3	101 W3N3		
121 W5N3	102 W3AN3	REP1
120 W5N0	103 W3N0		
119 W1N0	104 W1AN3		
118 W3N0	105 W1N3		
117 W5AN3	106 W5N3	REP2
116 W3N3	107 W5N0		
115 W5AN3	108 W1N0		
114 W5N0	109 W5N3		
113 W1N3	110 W3N3	REP3
112 W3N0	111 W1N0		

Soybean 1990-91

1	12 Ibis	13
2	11 Impala	14
3	10 Hutton	15
4	9 Forrest	16
5	8 Ibis	17
6	7 Impala	18



Soybean 1991-92

HUTTON		21 19	3 20	14 21	21 22	14 23	3 24	
IMPALA			21 18	14 17	3 16	14 15	21 14	RAIN SHELTERS
HUTTON	14 7	3 8	3 L 9	21 10	21 L 11	21 12	14 13	
IMPALA		3 6	21 5	14 4	14 3	21 2	3 1	

Soybean 1992-93

HUTTON	3 / 26	14 / 27	21 / 28	
PRIMA	21 / 25	3 / 24	14 / 23	
HUTTON	21 / 19	14 / 20	3 / 21	21 / 22
PRIMA	14 / 18	21 / 17	3 / 16	21 / 15
HUTTON	14 / 11	3 / 12	3 / 13	14 / 14
PRIMA	14 / 10	3 / 9	3 / 8	14 / 7
HUTTON	21 / 4	21 / 5	14 / 6	
PRIMA	21 / 3	14 / 2	21 / 1	

RAIN SHELTERS

APPENDIX 2

Roodeplaat Weather Data

Computer# : 17254 Station name : ROODEPLAAT - AGR
Latitude : 2535 AMnumber : 0513/605 4
Longitude : 2821 District : PRETORIA
Altitude : 1164 (m)

LONGTERM SUMMARY OF AVET (°C) FOR 43 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	715.8	641.1	658.2	543.2	449.0	335.5	351.7	431.6	537.4	635.5	642.7	691.3
AVE	23.1	22.7	21.2	18.1	14.5	11.3	11.5	14.0	17.9	20.5	21.4	22.4
S.D.	1.9	1.7	1.9	2.2	2.2	2.2	1.9	2.5	2.9	2.8	2.5	2.1
HIGH	29.6	30.2	27.7	24.1	20.8	17.9	17.0	20.9	25.2	27.7	28.3	28.5
DATE	1992	1992	1984	1987	1979	1966	1979	1986	1978	1965	1952	1952
LOW	15.2	16.0	12.7	9.6	6.2	2.1	3.5	5.3	7.8	11.8	9.9	13.1
DATE	1972	1955	1976	1972	1974	1994	1967	1972	1974	1973	1968	1970

LONGTERM SUMMARY OF MAXT (°C) FOR 43 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	912.6	818.8	865.3	764.6	717.0	608.1	641.7	724.1	804.0	872.8	843.6	890.1
AVEX	33.9	33.1	32.2	29.9	27.4	24.8	24.8	28.9	32.7	34.3	33.9	33.7
AVE	29.5	29.0	27.9	25.5	23.1	20.3	20.7	23.4	26.8	28.2	28.1	28.8
S.D.	3.0	2.9	3.0	3.1	2.8	2.7	2.5	3.2	4.0	4.1	3.8	3.3
HIGH	37.6	37.9	36.4	33.1	29.9	31.0	26.6	34.6	34.7	42.3	37.1	37.2
DATE	1973	1983	1984	1987	1959	1953	1968	1981	1983	1954	1981	1957
LOW	17.0	17.0	15.4	13.4	12.4	7.9	10.6	9.2	9.7	13.4	11.6	16.2
DATE	1972	1955	1975	1972	1969	1964	1957	1983	1974	1973	1968	1966

LONGTERM SUMMARY OF MINT (°C) FOR 43 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	517.9	462.1	449.6	321.3	180.5	70.0	67.8	139.6	269.8	397.2	441.1	495.3
AVEN	12.4	12.2	9.8	5.2	0.2	-2.8	-2.7	-1.0	2.7	6.5	10.1	11.6
AVE	16.7	16.4	14.5	10.7	5.8	2.4	2.2	4.5	9.0	12.8	14.7	16.0
S.D.	2.1	2.1	2.3	2.9	2.9	3.1	2.8	3.2	3.4	3.0	2.5	2.3
HIGH	24.5	25.0	20.9	18.0	15.0	13.0	11.4	15.6	18.6	21.4	25.5	24.8
DATE	1953	1992	1963	1961	1985	1965	1993	1986	1966	1975	1952	1952
LOW	5.5	8.5	5.7	-0.1	-3.5	-7.4	-6.7	-5.9	-2.0	2.1	6.5	3.1
DATE	1960	1986	1974	1973	1994	1994	1988	1972	1959	1965	1988	1970

LONGTERM SUMMARY OF RAIN (mm) FOR 43 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	123.8	82.9	70.8	46.5	15.3	7.4	3.5	5.7	18.9	65.4	104.9	100.5
MAXM	414.7	212.3	209.5	151.2	186.7	62.8	57.0	42.1	98.7	158.7	203.0	192.4
DATE	1975	1980	1991	1963	1956	1989	1957	1979	1987	1964	1971	1966
MINM	15.0	19.1	13.2	0.0	0.0	0.0	0.0	0.0	0.0	8.8	16.0	22.7
DATE	1990	1960	1963	1956	1962	1953	1953	1953	1955	1965	1988	1978
AVE/W	9.8	8.2	7.7	7.7	6.2	5.2	3.7	4.1	6.5	8.5	9.0	8.5
S.D/W	14.2	10.4	11.1	10.8	8.6	8.2	7.2	6.6	7.8	11.8	11.7	10.6
HIGH	133.7	64.7	83.2	68.0	39.5	37.2	44.0	35.7	31.6	80.8	111.5	70.0
DATE	1975	1985	1967	1965	1956	1963	1957	1979	1987	1986	1955	1969
LOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DATE	1953	1953	1953	1953	1953	1952	1952	1952	1952	1952	1952	1952

LONGTERM SUMMARY OF EVAP (mm) FOR 38 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	240.4	205.1	194.2	152.4	132.2	109.7	144.6	170.5	221.6	251.9	253.4	248.6
AVE	8.0	7.4	6.4	5.2	4.3	3.7	4.7	5.5	7.4	8.2	8.6	8.1
S.D.	2.5	2.4	2.1	1.7	1.2	1.1	3.1	1.5	2.3	2.9	4.2	2.7
HIGH	19.0	19.5	13.6	12.5	9.5	10.0	25.0	13.0	14.5	17.5	33.2	18.5
DATE	1970	1967	1983	1959	1993	1971	1966	1970	1968	1962	1974	1984
LOW	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.6	0.0	0.0	0.0	0.1
DATE	1994	1989	1986	1988	1989	1957	1961	1981	1990	1986	1969	1990

LONGTERM SUMMARY OF SUNS (Hr) FOR 36 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	265.4	240.6	250.0	248.4	279.9	266.2	286.4	292.9	279.8	273.6	253.6	264.2
AVE	8.6	8.6	8.1	8.3	9.0	9.0	9.2	9.5	9.4	8.8	8.5	8.7
S.D.	3.5	3.4	3.1	2.9	2.0	1.8	1.6	2.0	2.5	3.2	3.6	3.5
HIGH	13.3	13.0	12.1	11.5	10.9	10.6	10.8	11.3	11.6	13.0	13.3	13.7
DATE	1959	1978	1985	1961	1959	1961	1961	1970	1960	1992	1969	1990
LOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DATE	1962	1966	1960	1960	1968	1963	1961	1967	1965	1962	1960	1960

LONGTERM SUMMARY OF WIND (Km) FOR 36 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	2822.6	2496.2	2566.5	2415.5	2538.1	2494.9	2646.4	2984.5	3074.3	3384.4	3184.7	3014.9
AVE	91.2	88.4	83.2	80.7	82.0	83.3	85.6	96.6	102.6	109.5	106.2	98.8
S.D.	56.6	51.2	44.5	41.9	44.7	45.4	46.8	61.0	70.4	76.9	69.2	60.9
HIGH	510.8	275.6	256.2	265.3	306.5	316.2	353.8	484.7	421.3	456.7	391.6	328.6
DATE	1979	1983	1992	1985	1979	1984	1959	1959	1981	1959	1983	1984
LOW	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.5	0.0	0.2	0.2	0.0
DATE	1963	1968	1962	1963	1960	1973	1972	1972	1963	1969	1973	1962

LONGTERM SUMMARY OF MAXH (%) FOR 17 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	2672.6	2440.3	2683.7	2564.5	2520.0	2445.5	2380.6	2245.6	2126.5	2390.9	2451.1	2639.6
AVE	86.2	87.0	87.9	87.9	83.5	82.3	76.9	72.6	70.9	77.3	82.0	85.5
S.D.	8.7	7.7	7.3	7.0	10.6	11.7	14.5	16.7	17.3	14.5	11.9	9.2
HIGH	97.0	98.0	98.0	100.0	100.0	100.0	98.0	98.0	97.0	97.0	97.0	98.0
DATE	1979	1985	1985	1993	1993	1993	1978	1984	1984	1978	1978	1986
LOW	27.0	51.0	49.0	56.0	36.0	32.0	28.0	24.0	15.0	26.0	41.0	14.0
DATE	1993	1992	1992	1982	1992	1992	1992	1982	1992	1990	1990	1992

LONGTERM SUMMARY OF MINH (%) FOR 17 YEARS ENDING 1994

	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TOT	947.8	914.5	962.5	798.7	705.2	685.9	667.2	634.8	601.8	749.2	849.8	919.7
AVE	30.6	32.6	31.0	27.7	23.3	23.0	21.6	20.6	20.2	24.3	29.1	29.7
S.D.	10.8	12.6	12.2	10.7	9.0	9.3	8.9	9.9	11.3	12.4	13.3	10.1
HIGH	91.0	75.0	82.0	73.0	75.0	71.0	59.0	63.0	75.0	81.0	89.0	77.0
DATE	1994	1978	1984	1984	1979	1989	1984	1983	1988	1993	1979	1990
LOW	3.0	7.0	7.0	6.0	1.0	2.0	1.0	1.0	0.0	2.0	4.0	5.0
DATE	1993	1992	1992	1992	1992	1992	1992	1988	1990	1991	1990	1992

APPENDIX 3 Example BEWAB Printout

Identification: ROODEPLAAT

Water application programme and minimum effective irrigation demands (IRR,mm) per cycle for WHEAT(150) with a seed target yield of 8000 kg/ha:

Days after planting	Complete CWD addition during peak		Partial crop water demand (CWD) addition during peak consumption (End season with dry soil): Profile completely wet at planting		Profile partially wet at planting		Profile dry at planting	
	IRR	Total	IRR	Total	IRR	Total	IRR	Total
10.	1.	1.	1.	1.	4.	4.	5.	5.
17.	5.	6.	5.	6.	27.	31.	32.	37.
24.	8.	14.	8.	14.	27.	58.	32.	69.
31.	12.	26.	12.	26.	27.	85.	32.	101.
38.	16.	42.	16.	42.	27.	112.	32.	133.
45.	22.	64.	22.	64.	27.	139.	32.	165.
52.	27.	91.	27.	91.	27.	166.	32.	197.
59.	33.	124.	33.	124.	27.	193.	32.	229.
66.	38.	162.	38.	162.	27.	221.	32.	261.
73.	44.	206.	43.	206.	32.	253.	36.	296.
80.	49.	254.	45.	250.	45.	297.	45.	341.
87.	53.	307.	45.	295.	45.	342.	45.	385.
94.	56.	363.	45.	339.	45.	386.	45.	430.
101.	58.	421.	45.	384.	45.	431.	45.	474.
108.	58.	479.	45.	428.	45.	475.	45.	519.
115.	57.	536.	45.	473.	45.	520.	45.	563.
122.	54.	590.	45.	517.	45.	564.	45.	608.
129.	49.	638.	45.	562.	45.	609.	45.	652.
136.	41.	680.	41.	603.	41.	650.	41.	694.
143.	31.	711.	31.	634.	31.	681.	31.	725.
150.	18.	729.	18.	653.	18.	700.	18.	743.

COMMENTS

Profile available water capacity during peak consumption = 116.2628 mm
Reserved rain storage capacity = 30 mm
(The rain more than IRR mm per occasion should not be taken into account if the complete addition option is used.)
Useable profile available water during peak consumption = 86.26284 mm
The irrigation system has to be able to effectively apply:
8.300943 mm/day for the complete CWD addition option and
6.357896 mm/day for the partial addition option.

Profile depletion starts on day 71

Appendix 4 Summary of Grain Yield and Seasonal Water Use Means for all Treatments in the Four Linesource Wheat Experiments.

			GRAIN YIELD (kg/ha)														
	Irrigation		W1			W2			W3			W4			W5		
YEAR	Frequency		Side: 1	2	BOTH	1	2	BOTH	1	2	BOTH	1	2	BOTH	1	2	BOTH
1990	Weekly	N0	2382	2582	2448	3054	3173	3094	4242	3176	3887	4560	3511	4210	3413	3560	3462
		N1	1852	3356	2353	4048	2147	3414	5987	2236	4737	6006	4061	5358	6088	5075	5751
		N2	2131	3485	2582	4509	3433	4150	5237	4995	5156	6677	6989	6781	5651	5842	5715
		N3	2741	2674	2719	4190	3344	3908	6628	4513	5923	7115	4539	6256	6654	6564	6624
		N4	2569	2147	2428	4549	3173	4091	6270	4578	5706	6680	4887	6082	7255	6637	7049
1990	Two-weekly	N0	1828	1401	1543	2565	1781	2042	2735	2268	2424	2234	4905	4015	2052	4167	3462
		N1	1309	2062	1811	2710	1931	2191	4481	5665	5271	3913	5265	4814	3412	4979	4457
		N2	1364	1773	1636	4626	3210	3682	5181	4695	4857	6543	6667	6626	6357	7164	6895
		N3	1019	1865	1583	3842	2546	2978	5021	4390	4600	6615	5990	6198	6157	8436	7676
		N4	525	1570	1222	3706	1998	2568	5162	2913	3663	6104	7151	6802	3985	7612	6403
						LOW	HIGH		LOW	HIGH							
1991	Weekly	N0	2179	2642	2410	3099	3016	3058	6271	4428	5350	3335	3308	3322	3049	3436	3243
		N1	2252	2695	2473	3063	4175	3619	5538	5200	5369	6665	4972	5818	5136	4915	5025
		N2	2429	3432	2931	3160	4349	3754	6197	6324	6261	7650	7030	7340	6908	7622	7265
		N3	2136	3337	2736	2856	4895	3875	5572	7172	6372	7827	7126	7477	8180	7142	7661
		N4	2159	2519	2339	3670	5129	4399	6248	6535	6392	6864	6763	6814	7813	7309	7561
						LOW	HIGH		LOW	HIGH							
1991	Two-weekly	N0	2376	2618	2497	3348	3871	3610	3501	3766	3633	4033	2274	3154	3951	2975	3463
		N1	2202	2879	2540	2715	6772	4744	4418	6010	5214	5640	5637	5639	5953	5968	5960
		N2	2334	3179	2756	3292	5505	4399	5310	6865	6087	8303	6921	7612	7105	8715	7910
		N3	2665	3094	2880	2784	5256	4020	5895	7563	6729	9592	8110	8851	8332	9463	8897
		N4	2349	2937	2643	2623	5934	4279	5417	7667	6542	8549	8963	8756	9013	8225	8619
						LOW	HIGH		LOW	HIGH							
1992	Weekly	N0	1887	2890	2389	2958	5125	4041	4622	5664	5143	7102	6263	6683	6842	6209	6526
		N1	2218	3170	2694	3099	5684	4391	5483	6839	6161	6879	6701	6790	6351	4435	5393
		N2	2509	2890	2699	2514	5122	3818	4932	7921	6427	7548	7144	7346	5718	6475	6096
		N3	2435	2975	2705	2706	4342	3524	5658	6820	6239	7190	7560	7375	6478	6834	6656
		N4	2130	2706	2418	2887	5800	4343	5077	7003	6040	7176	5105	6140	8390	6644	7517
						LOW	HIGH		LOW	HIGH							
1993	Weekly	N0	2432	2365	2398	1707	4051	2879	2568	4560	3564	4193	4483	4338	4373	3712	4043
		N1	2537	2255	2396	1797	4698	3247	2834	5713	4273	5664	6862	6263	7043	7260	7151
		N2	2881	2608	2744	1983	5105	3544	4063	6967	5515	6617	6390	6503	7602	6540	7071
		N3	2786	2681	2733	1848	5365	3606	3209	7769	5489	6664	7840	7252	7772	7532	7652
		N4	2068	2648	2358	2017	5964	3990	3238	7405	5321	7710	7091	7400	6972	6882	6927

Appendix 4 (continued)

YEAR	Irrigation Frequency		SEASONAL WATER USE (mm) W1 Side: 1	W1 2	W1 BOTH	W2 1	W2 2	W2 BOTH	W3 1	W3 2	W3 BOTH	W4 1	W4 2	W4 BOTH	W5 1	W5 2	W5 BOTH
1990	Weekly	N0	184	196	188	249	248	248	325	368	339	439	448	442	538	524	533
		N1	160	329	216	248	240	245	354	370	359	438	463	446	500	544	515
		N2	158	207	174	265	430	320	383	418	395	488	472	483	679	552	637
		N3	168	308	215	231	302	255	333	528	398	479	484	480	557	584	566
		N4	169	172	170	278	329	295	357	515	410	460	512	477	600	614	605
1990	Two-weekly	N0	186	149	161	198	235	222	302	310	307	364	440	414	488	513	505
		N1	158	166	163	262	211	228	301	343	329	395	439	424	449	542	511
		N2	126	199	175	228	234	232	352	333	339	337	427	397	454	477	469
		N3	96	129	118	195	363	307	263	327	306	413	274	320	475	556	529
		N4	158	137	144	154	207	189	319	308	312	406	425	418	497	519	512
						LOW	HIGH		LOW	HIGH							
1991	Weekly	N0	202	176	189	296	243	270	428	409	418	534	501	518	643	668	655
		N1	200	173	186	297	275	286	479	417	448	553	541	547	685	664	674
		N2	195	168	181	317	267	292	440	435	438	597	577	587	730	646	688
		N3	185	155	170	315	301	308	456	442	449	605	571	588	735	721	728
		N4	189	171	180	311	284	298	458	430	444	609	602	605	717	704	710
						LOW	HIGH		LOW	HIGH							
1991	Two-weekly	N0	205	174	189	277	284	281	380	351	365	430	448	439	573	537	555
		N1	193	164	178	272	409	340	410	391	400	473	463	468	548	544	546
		N2	198	187	192	285	296	290	410	450	430	512	493	502	561	577	569
		N3	207	189	198	283	281	282	437	432	435	527	520	523	632	626	629
		N4	194	190	192	283	299	291	432	458	445	559	426	492	567	616	592
						LOW	HIGH		LOW	HIGH							
1992	Weekly	N0	177	231	204	230	382	306	388	462	425	538	622	580	674	713	694
		N1	188	224	206	249	405	327	384	485	434	531	558	545	634	626	630
		N2	172	222	197	229	376	302	389	523	456	527	595	561	627	671	649
		N3	175	230	202	234	348	291	414	502	458	531	593	562	658	675	666
		N4	168	233	200	222	396	309	407	490	448	511	581	546	642	696	669
						LOW	HIGH		LOW	HIGH							
1993	Weekly	N0	211	227	219	250	332	291	396	460	428	497	594	545	664	739	701
		N1	214	219	217	244	354	299	333	484	408	557	619	588	663	743	703
		N2	211	262	236	277	409	343	379	478	429	530	595	562	721	753	737
		N3	209	256	232	256	380	318	379	428	404	610	663	636	668	748	708
		N4	233	237	235	303	348	325	317	494	405	518	675	596	676	727	701

APPENDIX 5

Details of Data Storage and Availability

A database has been established to archive the vast amount of data collected during this project.

The data are stored in the form of LOTUS 123, QUATTRO PRO or TEXT files. Each file has a unique name to allow for easy identification, and the files are located in a well-structured directory tree to allow for easy access. In some cases, unprocessed (raw) and processed data files exist for individual measurements/treatments, with other files summarizing means for the whole season. Chapter 3, Table 3.5 summarizes the measurements for which data are available.

Anyone wishing to make use of any part the data should apply to Dr. Sue Walker at:

Institute for Soil, Climate and Water
Private Bag X79
PRETORIA 0001

TEL. (012) 326 4205
FAX. (012) 323 1157

If any value is added to the data then a fee may be charged.

Permission must be obtained from ISCW if the information is to be published.

APPENDIX 6

List of Personnel involved in the Project

	QUALIFICATION	DATES WORKED ON PROJECT
Project leader		
S. Walker	PhD (Calif. Davis, USA)	01/90-end
Researchers		
A.J. Fourie	MSc Agric.	Planning stages
T.P. Fyfield	PhD (Reading, UK)	02/91-end
E.C. Koekemoer	BSc Agric. Hons	01/90-12/90
J.P.A. McDonald	BSc Agric. Hons	01/90-end
A.A. Nel	MSc Agric.	01/90-10/90
D.E. Ras	BSc Agric. Hons	01/90-09/91
A. (de Kock) Thackrah	BSc Agric. Hons	07/91-end
L.D. van Rensburg	MSc Agric.	Planning stages
Chief Technician		
L. Peense	Dip.	01/90-end
Technical Staff		
V. Bonnette	Dip.	02/91-04/94
E.O. de Wet	Dip.	01/91-end
E.E. (Roux) du Toit	BSc	01/90-05/90
H. du Toit	Dip.	12/92-end
J.U.V. Fourie	Dip.	01/91-01/92
K.J. Hlatswayo		01/90-end
L. (Putter) Kampman	BSc	01/90-06/90
E.C. le Roux	Dip.	12/91-12/93
M. Madisene		01/90-end
M.J. Maine		01/90-end
L.J. Malherbe	BSc	06/92-08/92
R.J. Maluleka		01/90-end
Z.M. Makopo		01/90-end
D. Moremi		01/90-end
M.A. Mothlabya		01/90-end
L.N. Mtshweni		01/90-end
J.C. Schmidt	H.Dip.	01/91-12/91
F.P. Sithole		01/90-end
H.G. Viljoen	Dip.	01/90-12/90

Visiting Researchers

Y. Cohen	PhD	24/08/90-06/10/90

Institute for Soils and Water
Volcani Center
ISRAEL

D.M. Oosterhuis	PhD	14/07/91-26/08/91

University of Arkansas
USA

G.S. McMaster	PhD	22/04/93-06/06/93

USDA
Fort Collins
Colorado
USA

APPENDIX 7

List of Publications and Papers Presented

OOSTERHUIS, D.M. & WALKER, S., 1992. Photosynthesis during wheat leaf development and effects of water and nitrogen stress. *Arkansas Farm Research* 41, 13-14.

S.A. Crop Production Congress - Jan. 1991 in Stellenbosch

WALKER, S. Yield reduction due to defoliation of wheat.

S.A. Crop Production Congress - Jan. 1992 at Golden Gate

de KOCK, A., WALKER, S. & McDONALD J.P.A. Die invloed van water- en stikstoftoediening op massa en aarverspreiding van koringkorrels.

McDONALD, J.P.A., WALKER, S. & BENNIE, A.T.P. Koringopbrengs onder wisselende water- en stikstofregimes.

WALKER S. & OOSTERHUIS, D.M. Efficient measurement of photosynthesis of field-grown irrigated wheat.

WALKER S. & OOSTERHUIS, D.M. Wheat photosynthesis as a function of leaf age, water deficit and nitrogen deficiency.

Agrometeorology & Remote Sensing Symposium - Oct. 1992

THACKRAH, A., WALKER, S. & McDONALD, J.P.A. Fenologiese aspekte van die kalibrasie van CERES-wheat vir lentekoring.

<u>S.A. Crop Production Congress</u> - Jan. 1993 in Rustenburg

FYFIELD, T.P. & WALKER, S. The minirhizotron system for monitoring root growth.

FYFIELD, T.P. & WALKER, S. Use of the heat pulse method to measure transpiration.

THACKRAH, A., WALKER, S. & McDONALD, J.P.A. Voorspellingsvermoë van PUTU-wheat en CERES-wheat simulasiemodelle.

WALKER S. & OOSTERHUIS, D.M. Water stress effects on the nitrogen content - photosynthesis relationship in wheat leaves.

<u>S.A. Crop Production Congress</u> - Jan. 1994 at Cedara

FYFIELD, T.P. & WALKER, S. Comparison of the minirhizotron and core methods for monitoring root growth of wheat.

WALKER, S., McMASTER, G.S. & THACKRAH, A. What is SHOOTGRO?

WALKER, S., THACKRAH, A. & McMASTER, G.S. Predicting spring wheat growth and development under South African conditions using SHOOTGRO.