Studies on Irrigation Management Based on PAWC and Soil Water Monitoring

F M G Vanassche and M C Laker

WRC Report No. 166/1/89

RESEARCH ON IMPROVING IRRIGATION MANAGEMENT BASED ON SOIL WATER MONITORING AND DETAILED KNOWLEDGE OF PROFILE AVAILABLE WATER CAPACITIES

by

F.M.G. VANASSCHE and M.C. LAKER

Department of Soil Science

University of Fort Hare

in co-operation with

Department of Soil Science and Plant Nutrition

University of Pretoria

EXECUTIVE SUMMARY

WATER RESEARCH COMMISSION

PRETORIA MAY 1989

1 MOTIVATION AND OBJECTIVES

In two consecutive projects attention was focussed on determining meaningful values of plant available water capacities of soils. Plant available water capacity, a property of the soil-plant system which is of great importance for the design and operation of an irrigation system, had traditionally been determined by water retention measurements on soil samples in the laboratory. This did not always reliably reflect the field situation. The first project introduced the concept of using the plant itself to indicate the onset of first material stress (FMS), at which point the amount of water extracted from the soil profile between field capacity and the onset of stress, defined as the profile available water capacity (PAWC) could be determined. The two projects produced numerous values of PAWC for a wide range of soil types for several crops (wheat, maize, cotton, peas) in three climatic areas. Simple regression models for PAWC have been derived. Soils with silt plus clay contents of less than 20% behaved differently from soils with higher silt plus clay contents. The physiological criteria used to indicate FMS proved unreliable under conditions of high atmospheric demand, resulting in crop yield losses when irrigation scheduling was based on PAWC under such conditions.

The aims of the present project are:

(i) To develop improved criteria for the definition and determination of the lower limit of PAWC, especially under conditions of high evaporative demand. It was also aimed to find an explanation for the fluctuating pre-dawn leaf water potential (PLWP) patterns found by Boedt & Laker (1985).

(ii) To expand PAWC studies to include crops during early growth stages.

(iii) To determine the relative sensitivity of a few major crops to soil water stress at different growth stages, both in terms of vegetative growth and yield.

(iv) To derive guidelines for improved irrigation management, based upon soil water monitoring with neutron probes, PAWC data and water-yield relationships for selected crop/soil combinations.

(v) To test derived irrigation management guidelines under practical farming conditions with a view to technology transfer.

The research was conducted at the Cradock Experimental Station of the Department of Agriculture and Water Supply near Cradock in the Eastern Cape Province, Republic of South Africa.

There were several reasons for selecting the Cradock Experimental Station as venue for this research project. The most important ones are:

1. The research of Boedt & Laker (1985) left some unresolved questions regarding soil-plant-water relationships under conditions of high evaporative demand. This research, therefore, had to be conducted in an area with hot, dry summers.

2. The Cradock Experimental Station is situated in the Fish River valley, where intensive irrigation is practiced. Major irrigation expansion is expected in this region and the Cradock Experimental Station is climatologically and pedologically representative for the area.

3. The Cradock Experimental Station has good infra-structure for irrigation research.

4. The Cradock Experimental Station is situated only 160

km from the University of Fort Hare, making it possible for the project leader to maintain a fair degree of contact with the researcher between his lecturing and administrative duties at the University.

2 RESULTS

2.1 PAWC VALUES OF WHEAT, DURUM WHEAT AND MAIZE AT DIFFERENT GROWTH STAGES AND THE EFFECTS OF SOIL WATER STRESS AT DIFFERENT GROWTH STAGES ON VEGETATIVE GROWTH AND GRAIN YIELD

2.1.1 Wheat

Both stem elongation rate (SER) and PLWP patterns clearly indicated the onset of FMS during young growth stages. During later stages FMS was indicated only by PLWP. Almost all PLWP patterns showed the typical fluctuating phase at the end of the drying cycles.

Irrigation at the end of the drying cycles resulted in increased SER which sometimes exceeded those of the non-stressed plants if soil water stress had been induced during early vegetative growth stages.

2.1.3 Maize

Leaf expansion and PLWP clearly indicated FMS during the early vegetative stages. Once the plants were past the 16-leaf stage, PLWP values below -1000kPa clearly indicated FMS. Leaf expansion rates were not a reliable parameter for FMS from this growth stage onwards.

Stem elongation was a more sensitive parameter than leaf expansion. Stem elongation data could make the distinction between moderate and severe water stress and indicated water stress where leaf expansion failed.

Ceulemans, Impens, Laker, Vanassche & Mottram (1988) found that PLWP was not as sensible as the net carbon-dioxide exchange rate (NCER) for indicating FMS, especially under extreme climatic conditions. However, Ceulemans and co-workers based their conclusions on single, daily PLWP measurements. It is very important to realize that when using PLWP as an indicator for FMS daily measurements, starting as soon as possible after irrigation, must be used over an extended period.

The existence of a seasonal variation in PLWP was also found during this study. As the plants reach maturity, PLWP values

Although the yields obtained at the stressed plots were generally lower than those from the respective control plots, no statistically significant differences could be found.

2.1.2 Durum wheat

Both stem elongation and PLWP were very good indicators of FMS in young plants. At later growth stages stem elongation failed to indicate FMS, but PLWP indicated it very clearly. Great care has to be taken as to which leaves are selected for PLWP measurements. Tests have shown that young, immature leaves have lower PLWP values and could mistakenly be interpreted as an indication of FMS.

The PAWC values determined at the different growth stages indicated that the maximum PAWC value (PAWC at flowering stage) is already reached quite some time before flowering. This was also found in the case of wheat.

Water stress during the vegetative stages affected vegetative growth and yield severely. The detrimental effects of water stress during the vegetative stages on vegetative growth and especially on yield clearly show that water stress should be avoided.

tend to be lower than during the young vegetative stages, even under optimal conditions. This was also found with wheat and durum wheat.

PAWC values four during the 1986-1987 season showed that the maximum value is already reached at the 14-leaf stage, quite some time before flowering stage. This was not found during the 1985-1986 season, but doubts exist about the latter PAWC values. PAWC of maize was higher than that of wheat.

Although significant differences in vegetative growth as a result of water stress were found, no statistically significant differences in yield could be detected.

2.2 IRRIGATION SCHEDULING EXPERIMENTS

The quite good maize yields, averaging close to 10t/ha were achieved despite conditions, especially in regard to quality of the soil, that are apparently far from ideal for maize production.

PAWC, proved to be a reliable parameter for use in the design of irrigation scheduling strategies for maize. Yields were not reduced significantly even at extraction of 100% of

PAWC. Although extraction of 125% of PAWC for maize did not result in statistically significant lower yields, there was a consistent tendency for yields at this level of extraction to be somewhat lower than those for other treatments.

In contrast to the fairly good yields obtained with maize, the yields of wheat and durum wheat were moderate to poor, averaging 5t/ha. This was despite great care to optimize production conditions. In the case of wheat extraction of 100% of PAWC did not reduce yields.

Deficit irrigation failed to improve water use efficiencies based upon total water consumption (WUEt) for both maize and wheat. However, water use efficiencies based upon applied water (WUEi) were generally improved significantly by deficit irrigation practices. High frequency deficit irrigation around FMS (100% extraction of PAWC) gave better results than high frequency deficit irrigation combined with mild water extraction.

For both maize and wheat moderate water stress (extraction of 100% of PAWC) did not reduce yields at any growth stage. During the late vegetative stages even severe stress (125% of PAWC extracted) did not reduce yields. Severe water stress at the flowering and grain filling stages reduced yields in both crops, although the reductions were not always statistically significant. The reductions during the grain filling stages were particularly severe.

3 CONCLUSIONS

The present study clearly indicated that PLWP is a reliable parameter for identification of FMS in both immature and mature plants. A standardized procedure for PLWP measurements, described in this report, proved to be very reliable and yielded highly reproducible results. This study, therefore, offers the reader a reliable technique for PAWC determinations for a crop at any growth stage.

The present study also clearly proved that deficit irrigation can be applied successfully during peak demand periods without reducing yields or irrigation water use efficiencies. In fact, deficit irrigation generally gave higher irrigation water use efficiencies than full irrigations.

The fact that deficit irrigations at soil water contents close to FMS had no harmful effects on yield and water use efficiencies is ample proof of the validity of the PAWC concept for irrigation scheduling.

4 RECOMMENDATIONS

4.1 RESEARCH

Intensive studies on the effects of water stress during young growth stages on root development are required. Direct root growth monitoring will indicate how and where in the profile root growth is increased as a result of water stress. These experiments could easily be done in laboratories by using soil columns.

Detailed studies on soil water uptake by means of a highly accurate soil water content measuring apparatus could lead to some interesting results. This type of research will indicate from which parts of the profile water is extracted at different degrees of soil water content, especially near field capacity. These experiments should be done in laboratories and if possible in a controlled growth chamber.

More research on the combined effects of salinity and the type of irrigation scheduling is required.

More research on deficit irrigation applications is recommended.

4.2 PRACTICAL ON-FARM SCHEDULING

Because the validity of the PAWC concept together with deficit irrigation scheduling has amply been proven and because water is the most important and simultaneously the limiting factor for agriculture in South Africa, the following recommendation can be put forward: Extension officers, who are the main link for transfer of knowledge to the farmers, should make it their task to promote the PAWC concept and its use in practical irrigation scheduling. This can be done by the creation of technical centra which could determine PAWC of specific crops on specific soils all over the country. The results would then be used to establish irrigation scheduling programmes for each crop and for each soil or region while also taking into consideration the technical possibilities of the farms in question.

In view of the results obtained during the irrigation scheduling experiments the following conclusions and recommendations can be given:

1. Extending intervals between irrigations will improve water use efficiencies and save considerable amounts of water and capital. However, soil water extraction should not exceed 100% of PAWC (for the specific crop and soil) as this would reduce yields to economically unacceptable levels.

2. Deficit irrigation will improve water use efficiencies without the risk of inducing water stress. This, again, means a considerable saving of water and capital input but with a lower risk of yield reductions.

3. If water supply is severely limited and crops will inevitably experience water stress at some stage during the growing season, then irrigations could be postponed during vegetative stages in order to save water and ensure an adequate amount of water in the soil profile during flowering and grain filling stages (moderate water stress during part of the latter is acceptable but not recommended).

REFERENCES

BOEDT, L.J.J. & M.C. LAKER, 1985. The development of profile available water capacity models. Alice: University of Fort Hare.

CEULEMANS, R., I. IMPENS, M.C. LAKER, F.M.G. VANASSCHE & R. MOTTRAM, 1988. Net CO2 exchange rate as a sensitive indicator of plant water status in corn (Zea mays L.). Can. J. Plant Sci. 68, 597-606.

ABSTRACT

Profile available water capacities (PAWC) for wheat, durum wheat and maize at different growth stages were determined on a variety of soils at the Cradock Agricultural Research Station. This was done following the guidelines proposed by Hensley & De Jager (1982) and Boedt & Laker (1985). Pre-dawn leaf water potential (PLWP) could be used to indicate first material stress in both young and mature plants - except under conditions of high evaporative demand. However, it was found that relatively higher PLWP values indicated first material stress during young growth stages.

Plant performance related parameters, such as stem elongation and leaf expansion, were also used to identify first material stress during the vegetative stages. Leaf expansion measurements with maize led to the definition of a leaf area parameter. During the experiments a relationship between leaf length and leaf width was found. This relationship was further investigated and resulted in a relationship between leaf length and leaf area parameter. Finally, a formula was derived to convert leaf length into leaf area index (LAI) which is the ratio

of leaf surface to ground surface available to the plant.

Results obtained from leaf water potential readings on durum wheat emphasized the necessity of standardizing the procedure for leaf water potential measurements up to the point of leaf selection. The procedure worked out during this study gave reliable and reproducible results.

The effects of water stress at different growth stages was studied by monitoring vegetative growth and by determining yield. Stem elongation in wheat and durum wheat was very sensitive to water stress. Wheat and durum wheat behaved differently under water stress conditions. Reductions in stem elongation as a result of water stress were permanent in durum wheat. Upon rewatering an increased stem elongation, in some cases exceeding that of well-watered plots, was measured in wheat during the early growth stages. An intensive study on the effects of water stress on the stem elongation and leaf expansion rates of maize yielded some interesting results. Stem elongation proved to be more sensitive to soil water stress than leaf expansion. At the end of the growing season stem elongation measurements and interleaf distances could indicate if the plant had been subjected to moderate or severe soil water stress and also at what stage during the vegetative growing season.

The PAWC concept was evaluated by means of extensive comparative irrigation scheduling experiments. The emphasis was put on deficit irrigation as a logical sequence to the promising results obtained by Boedt & Laker (1985) with a deficit irrigation experiment. The validity of the PAWC concept was confirmed by the results obtained during the irrigation scheduling experiments. Deficit irrigation at soil water contents close to first material stress did not reduce yield significantly and improved water use efficiencies based on applied water (WUEi).

Some special investigations included a quick and simple method for delineation of filled up gullies, the relationship between yield and the amount of soluble salts, the effect of gypsum application on the leaching of soluble salts and the study of drainage curves.

The delineation of filled up gullies is important in research studies because it gives an idea of variations in the soil profile which can be responsible for differences within treatments.

The results of the study of the relationships between yield and the amount of soluble salts indicated that the degree of salinity has to be taken into account when developing an irrigation scheduling programme. High frequency deficit irrigation treatments combined with high degrees of salinity had a detrimental effect on yield which could be avoided by application of low frequency deficit irrigation treatments for which large amounts of water are applied at each irrigation.

Some recommendations for future research in the field of the behaviour of plants under water stress conditions and the effects of water stress as well as recommmendations for on-farm scheduling are made in Chapter 6.

ACKNOWLEDGEMENTS

The authors wish to express their sincere gratitude towards the following persons and institutions:

The Water Research Commission, for sponsoring the research project.

The Council and Rector of the University of Fort Hare, for permission to undertake the project and for providing administrative support.

The Rector of the University of Pretoria, for permission to Prof. Laker to remain project leader during the last two years of the project, when he was a staff member of that University.

The project steering committee, and especially Drs. G.C. Green and P.C. Reid, who acted as chairmen at different stages, for their highly appreciated support and extremely valuable criticisms.

The Director of the Karoo Region of the Department of Agriculture, for permission to conduct the research at the Cradock Agricultural Research Station and for the continued interest and valuable support of several of his senior staff members, especially mr. G.C. de Kock and mr. P.S. van Heerden.

The staff of the Cradock Agricultural Research Station, for their valuable support during the field experiments, and especially mr. A.G. Bezuidenhout for his friendly co-operation at all times.

Mr. J.H. Pretorius, of the Cradock Agricultural Research Station, for his valuable information and advice regarding agricultural practices and friendly co-operation.

Mrs. E.S. Vanassche, for the enthusiasm with which she co-operated in the field work and with which she calculated the collected data and helped with the drawing of the diagrams.

The Department of Soil Science and Plant nutrition of the University of Pretoria, for the permission to use their laboratory facilities.

Mrs. M. Buscop, of the Department of Soil Science and Plant Nutrition at the University of Pretoria, for assisting in the finalizing of the diagrams.

Mr. C.E.P. Lemaire, for preparing the experimental sites and planting and caring for the 1985 winter experiments until the researcher assumed duties in August 1985.

C O N T E N T S

LIST OF ABBREVIATIONS USED IN THIS REPORT

AET : Actual evapotranspiration
CWSI : Crop water stress index
FC : Field capacity
FMS : First material stress
gs : Stomatal diffusion conductance
LAI : Leaf area index
LAP : Leaf area parameter
LER : Leaf expansion rate
LOL : Lower limit (measured in situ)
LSD : Least significant difference
LWP : Leaf water potential
NCER : Net carbon-dioxide exchange rate
PAR : Photosynthetically active radiation
PAW : Plant available water
PAWC : Profile available water capacity
PET : Potential evapotranspiration
PEW : Profile extractable water
PLEXW : Potential extractable soil water
PLWP : Pre-dawn leaf water potential
PPFD : Photosynthetic photon flux density
SER : Stem elongation rate
SPAC : Soil - plant - atmosphere - continuum
T : Temperature
Ta : Air temperature
Tl : Leaf temperature
VSD : Vapour saturation deficit
WUE : Water use efficiency
WUEi : Water use efficiency calculated for applied water
WUEt : Water use efficiency calculated for total consumption

CHAPTER 1

THE EFFECTS OF SOIL WATER STRESS ON PLANT GROWTH AND PRODUCTION

1.1 INTRODUCTION

It is very important to understand the long term effects caused by water stress on growth and yield of plants. Growth and yield are the result of biological processes that are regulated by internal and external factors. Among the external or environmental factors, water is the most limiting on a global basis. Environmental water deficits modify the biological and physiological processes of plants and reduce plant growth and yield (Kramer, 1969). A better knowledge of the effects of water deficits in plants on growth and yield should contribute towards improved irrigation efficiencies and practices, growing of cultivars with higher water use efficiencies and development of effective dry-land agriculture (Hsiao, Fereres, Acevedo & Henderson, 1976).

An increasing degree of water shortages for agriculture caused by drought hazards and a stiffer competition from urban and industrial areas, necessitates alternative agricultural practices. Previously, irrigation was supplied to meet maximum demands but in future this tendency will have to change to reaching higher water use efficiencies (Hanks & Rasmussen, 1982).

One way to eliminate or minimize harmful effects of water shortages is to maximize water use efficiencies. This requires answers to both questions of when to irrigate and how much water to apply during a specific irrigation. The answers to both these questions are determined by a combination of the sensitivity of the specific crop to water stress during specific growth stages (and its impact on yield) and the water storage capacity of the soil between field capacity and the water content at which stress sets in. These questions have received the attention of a number of researchers, inter alia Hillel (1980), Ritchie (1981), Laker (1982), Hensley & De Jager (1982), Gardner (1983), Ratliff, Ritchie & Cassel (1983), Boedt & Laker (1985).

1.2 REVIEW OF LITERATURE

1.2.1. Water deficits in plants

Kramer (1969) defines a water deficit in a plant as follows: " Water deficit refers to situations where cells and tissues are less than fully turgid." There are various degrees of water deficits in plants. It can vary from a small decrease in water potential, detectable only by instrumental measurements, through transient midday wilting, to permanent wilting and death by desiccation. Water deficit is characterized by a decrease in water content and osmotic potential, resulting in a loss of turgor, partial or total closure of the stomata and decrease in growth. Severe water deficits will reduce photosynthesis, disturb other physiological processes, stop growth or result in death by desiccation.

Plant water deficits are caused either by excessive loss of water (transpiration) or inadequate absorption (soil water stress), or a combination of both. In other words, whenever the loss of water in transpiration exceeds the rate of absorption, water deficits occur (Kramer, 1969). Midday water deficits are caused by the absorption lag

(Figure 1.1). Absorption tends to lag behind transpiration because of a resistance to water flow through plants and also because the rates of absorption and transpiration are controlled by different factors. Leaf area, stomatal opening and the vapour pressure gradient from plant to air control the transpiration rate, while the rate of water loss, the extent and efficiency of the root system, and soil water potential and hydraulic conductivity control the absorption rate. The parenchyma tissue acts as a buffer in this system by losing water when transpiration exceeds absorption and gaining water in the reverse conditions. This results in an initial decrease in leaf water content and loss of turgidity when the transpiration rate is high, often culminating in wilting (Kramer, 1969).

As described above, water loss by transpiration is the primary cause of temporary midday plant water deficits. However, long periods of severe water stress are mainly caused by a decreased absorption rate due to a decreasing availability of soil water. This proces was intensively studied by Slatyer (1967). Transpiration from a plant, rooted in an initially wet soil will progressively reduce the soil water content and the soil water potential. The reduction of the soil water potential will result in a reduction of plant water potential and plant water

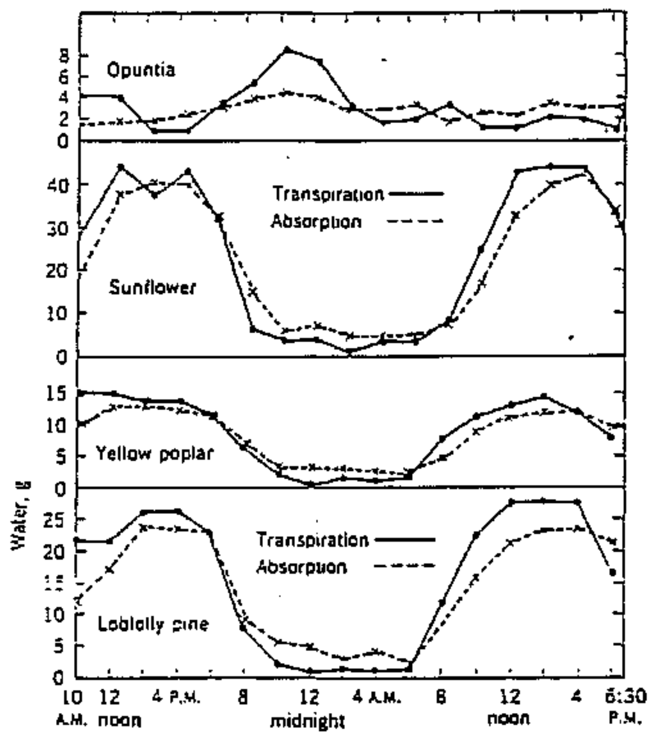


FIG. 1.1 Absorption lag in four different plant species. The soil was watered with an auto-irrigation system which allowed the measurement of water absorption. The midday drop in transpiration of sunflower is caused by loss of turgor and midday closure of the stomata. From Kramer, 1969.

content. The reason for this is the necessity of a gradient of decreasing potential through the water pathway in the soil-plant-atmosphere continuum (Slatyer, 1967). The decreasing soil water content and potential will result in an internal plant water deficit which will increase in magnitude as long as no soil water is added. This proces is illustrated in Figure 1.2. The diagram also shows a diurnal rhythm in the plant water potential superimposed on the general level and which is caused by the absorption lag.

The diurnal cycle of the leaf water potential is mainly controlled by the transpiration rate while the general decrease of the plant water potential is mainly controlled by the soil water potential and soil water conductivity, both being closely related to the soil water content. The upper limiting curve in Figure 1.2 shows the progressive decline in the soil water potential of a drying soil profile. The other curves show the root water potential and the leaf water potential. When the soil is wet, only small differences between soil and root water potential are needed to maintain water flow. When transpiration stops, there is a fast recovery of the plant water potential until the leaf and root water potential are equal. By sunrise, the recovery is complete and soil, root, and leaf water potential are the same.

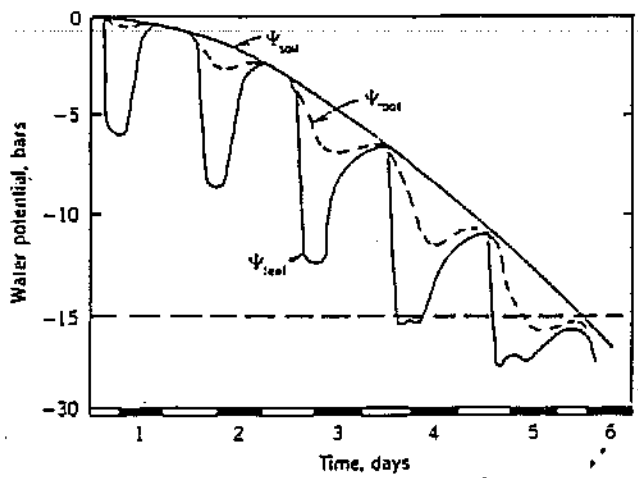


FIG. 1.2 Progressive decline of soil water potential and expected resulting changes in root and leaf water potential of a transpiring plant rooted in an originally wet soil. The dark bars represent darkness. From Slatyer, 1969.

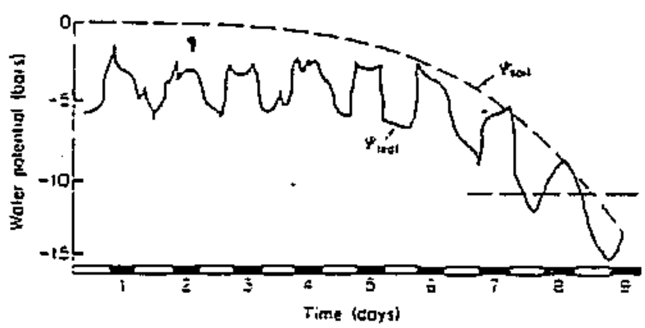


FIG. 1.3 Progressive decline in soil water potential and observed changes in leaf water potential of a pepper plant rooted in a clay loam soil under controlled evaporative conditions. From Gardner & Nieman, 1964.

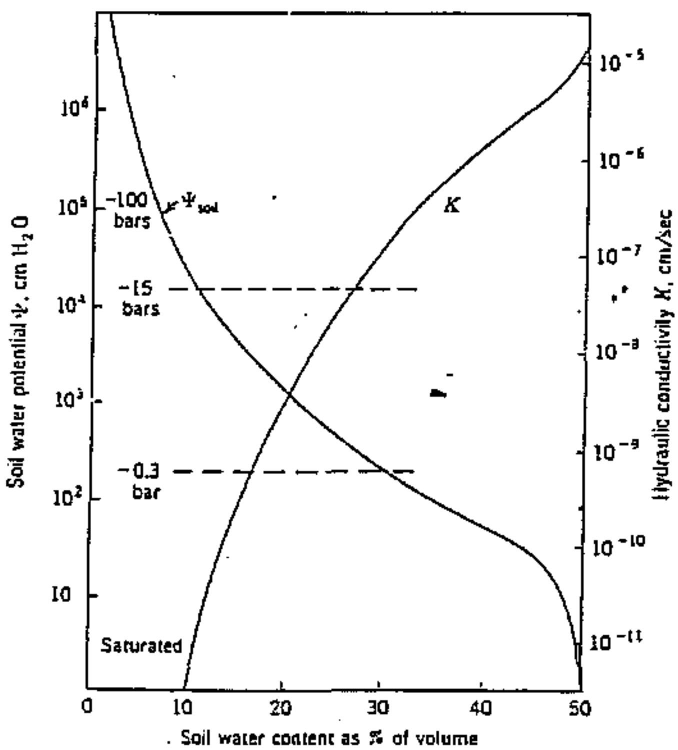


FIG. 1.4 Decrease in hydraulic conductivity and soil water potential with decrease in soil water content. From Philip, 1957.

However, as soil water content and potential decline, the soil water conductivity decreases even faster (Philip, 1957) and a much larger difference between root and soil water potential is required to sustain the flow and to replace transpiration losses (Figure 1.4). Also, recovery overnight becomes slower. When the plant water potential falls as low as the osmotic potential, the loss of turgor is accompanied by stomatal closure and wilting. When the leaf, root, and soil water potential are all equal and as low as the osmotic potential, the plant will be in a state of permanent wilting (Slatyer, 1967). This point is indicated on Figure 1.2 by the intersection of the potential curves and the horizontal line across the diagram. This diagram may be very schematic, but actual data obtained by Gardner & Nieman (1964) confirm it very well (Figure 1.3). Further confirmatory data were obtained by Slatyer (1967). A very close association between soil water, leaf water, and osmotic potentials was found when permanent wilting was observed in cotton, privet and tomato plants. Values of the osmotic pressure, leaf water potential, soil water potential and content are listed in Table 1.1.

TABLE 1.1 - Leaf osmotic potential, leaf water potential, soil water potential, and soil water content at first permanent wilting percentage (adapted from Slatyer, 1967)

Plant	osm. pot. kPa	leaf pot. kPa	soil pot. kPa	s.wat. cont %
tomato	-1800	-1900	-2000	11,8
privet	-4700	-4500	-4800	9,7
cotton	-3800	-4300	-3800	10,2

Slatyer (1967) concluded as follows: "From these data it appears that the permanent wilting percentage, rather than being a soil characteristic, is determined by the osmotic pressure of the leaf and is the soil water content corresponding to the soil water potential when the soil water potential, leaf water potential, and the negative value of the osmotic pressure are equal,so that there is a zero turgor pressure in the leaves of the plant being examined."

This conclusion contradicted the definition that the lower limit of plant available water was the water content in a soil subjected to a pressure potential of -1500kPa (Richards & Weaver, 1944). Permanent wilting point was considered to be a soil characteristic and at the same water potential for all soils and for all crops.

Hillel (1980) and Skaggs, Miller & Brooks (1982) confirmed Slatyer's conclusion when they found that some crops were wilting or some physiological functions were disturbed long before a soil water potential of -1500kPa was reached and at the same time that some crops could easily function at soil water potentials below -1500kPa.

In their definition of the lower limit of PAWC, Hensley & De Jager (1982), Hensley (1984) and Boedt & Laker (1985) used criteria related to plant performance or plant physiological processes, namely the leaf water potential. They also stressed the fact that the PAWC is different for different crops, growth stages, and soil profiles.

1.2.2 Effects of plant water deficits on physiological processes

It is well known that water deficits in plants will result in a considerable reduction in size and yield. Reduced cell turgor is the most important factor for reduced plant size. However, water deficits will also affect other physiological processes such as transpiration, photosynthesis, cell enlargement, and cell division (Hsiao et al., 1976). Larcher (1980) studied the sensitivity of different cell functions to water deficiency and changes in the plant as it dries out. He used the change in water potential as compared with that when there is a good supply of water to measure the stress induced by water deficiency (Figure 1.5). More recently Hsiao (1982) concentrated on the effect of water stress on source size rather than on intensity size (Figure 1.6). With regard to Figure 1.6 Hsiao states (according to Laker, 1983):

> "In the past attention has often been directed at effects of stress on source intensity. However, as figure 1.6 makes clear, the effects on source size are equally or even more critical. Source size is considerably more sensitive to water stress during the canopy development phase than is source intensity. Also, reductions in source size can be reversed only slowly, if at all, whereas source intensity usually recovers fully in a matter of one to a few days after water becomes available."

The effects on transpiration by water stress are caused by changes in stomatal aperture. Water deficits have a direct effect on stomatal aperture, by their effect on

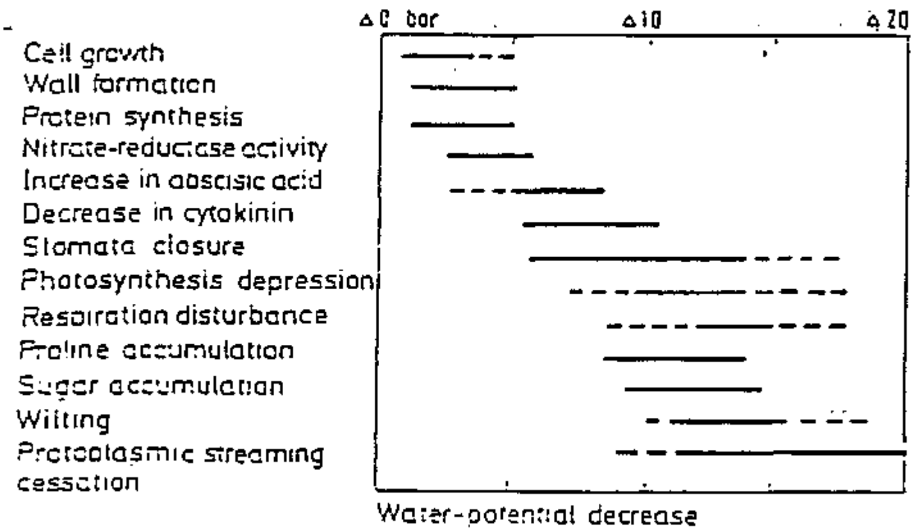


FIG. 1.5 Sensitivity of cell functions to water deficiency, and changes in the plant as it dries out. The lines indicate the range in which a clear effect begins to appear in most plant species. The measure of dessication stress used here is the change in water potential as compared with that when there is a good supply of water. From Larcher, 1980.

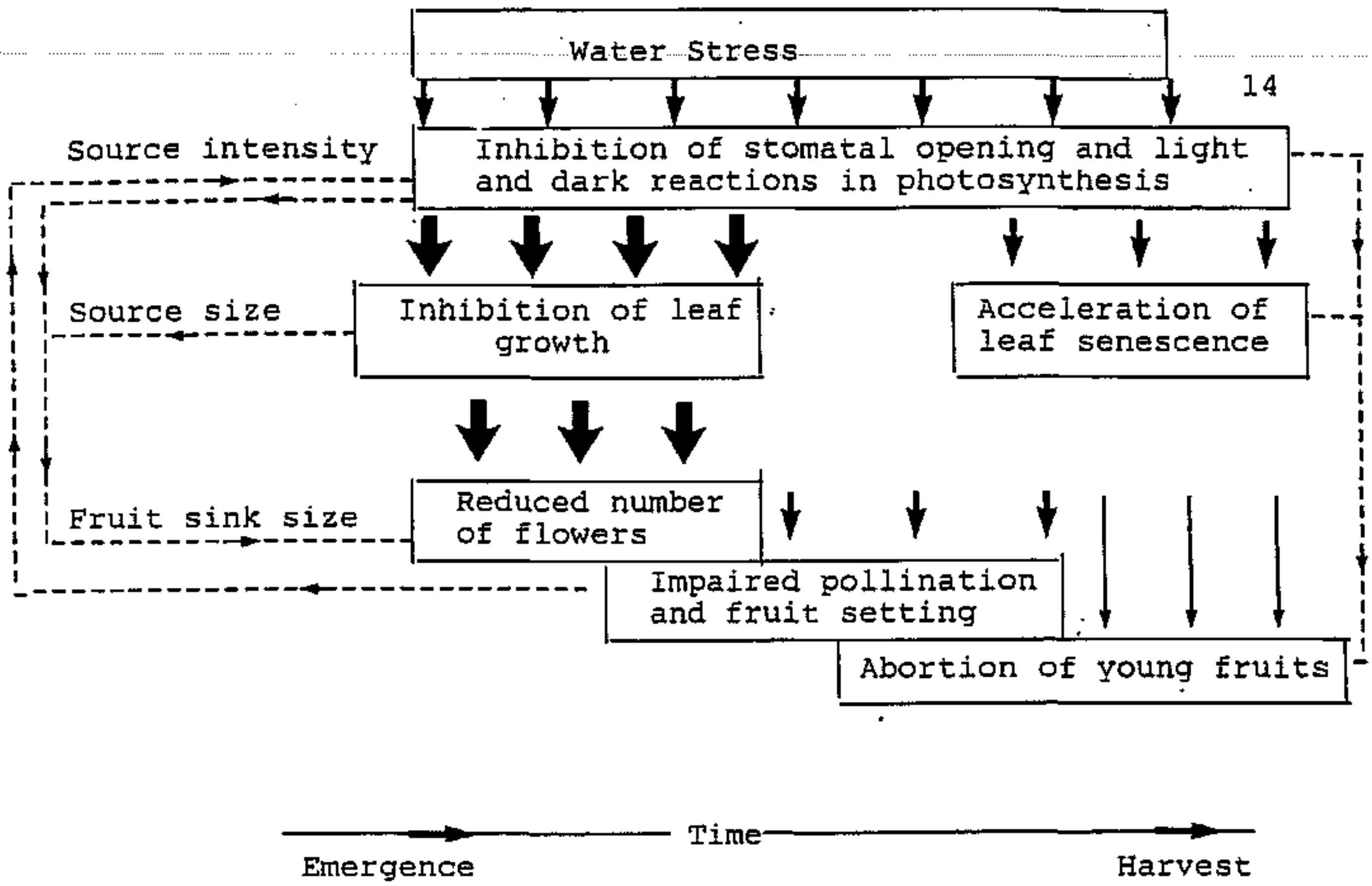


FIG. 1.6 Effects of water stress on the physiological and morphological parameters underlying source intensity, source size and sink for assimilation at various times of ontogeny, generalized for annual crops grown for grain or fruit. The time intervals within the crop ontogeny when water stress can cause physiological and morphological changes are indicated by the locations of the rectangles outlining the changes. Arrow shafts widths indicate the sensitivity of the parameters to water stress. For example, leaf growth is the most sensitive to stress and flower number is the next most sensitive. Dashed arrows and lines indicate casual relations among the parameters. For example, inhibition of leaf growth, of stomatal opening, and of photosynthesis results in fewer flowers being differentiated, probably because the number of reproductive axes is determined by plant size and the amount of assimilates available. Another example of casual relations is that impaired fruit setting reduces the number of sinks for assimilates and usually leads to a reduction in stomatal opening and photosynthesis via feedback inhibition. Adapted from Hsiao, 1982.

relative and absolute turgor levels in guard cells and surrounding cells (Stalfelt, 1961; Allerup, 1961; Ehlig & Gardner, 1964; Meidner, 1965). There are two types of reactions. The first one is a temporary change in stomatal aperture as a result of changes in guard cell turgor relative to that of the neighbouring cells. The second one is a longer term change caused by severe and prolonged water stress.

The first type is based on the hypothesis that adjacent epidermal cells tend to exchange water more rapidly with the atmosphere and vascular system than the guard cells themselves. An illustration of this is the changes in stomatal aperture which occur when a transpiring shoot is cut off. Results of an experiment by Meidner (1965) are illustrated in Figure 1.7. The first closing movement is the result of a small turgor increase in the adjacent cells. This is caused by a water flow into those cells after release of tension in the xylem elements following excision. Due to the interrupted water supply and the tendency for a faster evaporation from the adjacent cells, their turgor declines relatively to that in the guard cells, resulting in opening of the stomata. The second closing movement is caused by turgor loss in both guard and adjacent cells due to a water deficit.

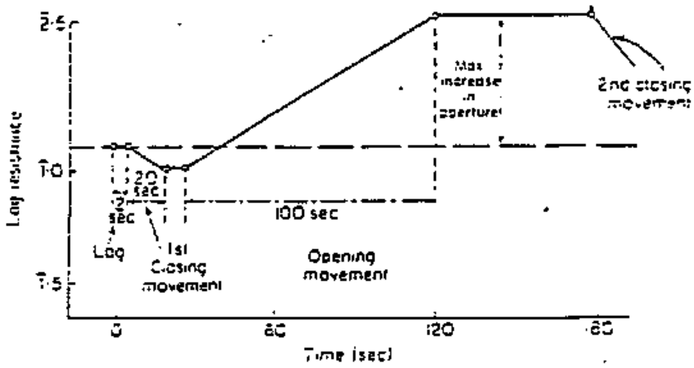


FIG. 1.7 Changes in stomatal aperture of a bean leaf (Phaseolus vulgaris) after excission from the plant. The stomatal aperture is expressed as log viscous air flow resistance. From Meidner, 1965.

The second type of reaction occurs at different values of the leaf water potential for different species, grown under different conditions (Stalfelt, 1961; Ehlig & Gardner, 1964). Water deficit will affect stomatal aperture when a critical value is reached and as the water stress becomes more severe, the stomata will progressively close until complete closure exists. This long-term effect is also influenced by increased internal carbon-dioxide levels caused by reduced photosynthesis.

The mechanisms described above are based on the relationship between leaf water content and stomatal activity. However, other investigators showed a relationship between soil water status and stomatal activity. Bates & Hall (1981), Turner, Schulze & Gollan (1985) and Blackman & Davies (1985) postulated that stomatal aperture was related to the soil water status and not to the leaf water status. Gollan, Passioura & Munns (1986) found evidence that the soil water status can influence the stomatal conductance but they denied that the leaf water status did not have any effect. Soil water status has an additional effect which is independent of the leaf water status. They concluded that this mechanism is based on a message sent by the roots to the leaves. Blackman & Davies (1985) and Davies, Metcalf, Lodge & Da Costa (1986) confirmed the existence of this message and explained it as a change of cytokinin supply to the leaves. Ceulemans, Laker & Vanassche (1988) confirmed that the soil water status is not the only factor when they found a large degree of stomatal closure in maize plants on a well-watered plot.

The interactive effects of nitrogen and water stresses on leaf water potential components, transpiration rate, and diffusive resistance of field grown maize was investigated by Bennet, Jones, Zur & Hammond (1986). They demonstrated that nitrogen and water stresses can interact within a field environment to alter water relations, stomatal activity, and transpiration of individual maize leaves. Leaves from nitrogen-sufficient plants were less affected by water stress than those from low-nitrogen plants. This was evidenced by maintenance of leaf turgor potential, relatively open stomata, and higher rates of leaf transpiration despite similar reductions in leaf water potential during periods of low soil water availability. As the leaf water potentials of both high- and low-nitrogen plants were more or less the same, the higher leaf turgor potentials in the high-nitrogen plants were the result of lower leaf osmotic potentials. Also, water extraction from the soil profile by water-stressed plants was more effective for the high-nitrogen plants.

The effects of water stress on photosynthesis are the consequences of many processes which are themselves affected by water deficits: reduction in leaf area, closure of the stomata, and a reduction of the protoplasmatic activity. To some investigators the reduction of photosynthetic surface and of the production of dry matter is the most important effect of water stress, but the reduction of photosynthesis per unit area must be considered too. This reduction, caused by water stress, is normally attributed to stomatal closure. The fact that transpiration and photosynthesis are often reduced to about the same extent supports this view (Brix, 1962; Barrs, 1968). This is illustrated in Figures 1.8 and 1.9.

However, Bierhuyzen & Slatyer (1964) and Slatyer (1967) claimed that there is an additional resistance in the carbon-dioxide pathway from the surfaces of the mesophyll cell walls to the photosynthesizing sites in the chloroplasts. This implies that for a given degree of stomatal closure the reduction in transpiration should be bigger than the reduction in carbon-dioxide uptake.

Indications that a dehydrated protoplasm, caused by water stress, can directly reduce photosynthesis were found by

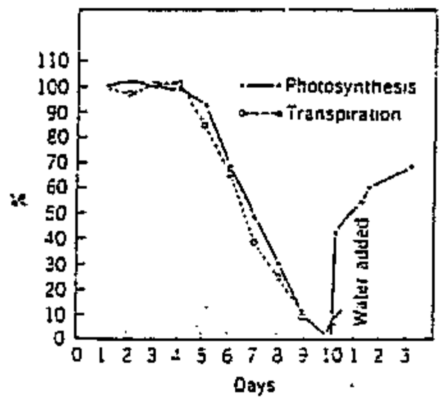


FIG. 1.8 Observed simultaneous decrease in rates of photosynthesis and transpiration of tomato plants subjected to increasing water stress and the return to normal after rewatering. From Brix, 1962.

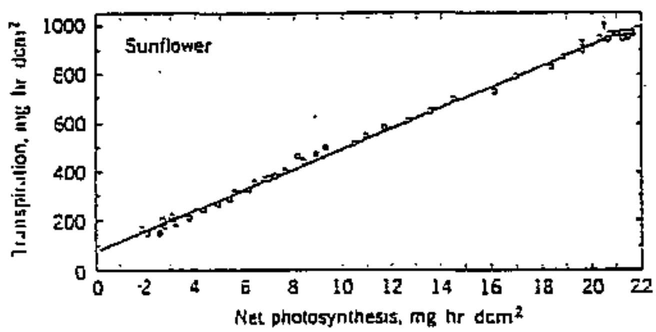


FIG. 1.9 Relation between transpiration and net photosynthesis of a drying sunflower leaf illustrating their simultaneous decrease. Points to the left of the arrow were obtained after excission. The simultaneous decrease is probably caused by closure of the stomata. From Barrs, 1968.

Boyer (1965). During an experiment with cotton, subjected to a high level of water stress but under such conditions that the stomata did not close, he found a substantial decrease in photosynthesis (Figure 1.10). Experiments with lower plants, which lack stomata, in aquatic solutions also showed a reduction in photosynthetic activity with increasing water stress (Greenfield, 1942).

Water deficit in plants causes a reduction in turgor pressure. This reduction has a dual effect. The first one, stomatal closure, has been discussed above. The second effect is a reduction in cell enlargement, which in turn will decrease shoot and root elongation and leaf enlargement. A direct consequence of the reduction in leaf enlargement is the reduction in photosynthetic surface.

Many investigators have demonstrated a close relationship between turgor pressure and leaf enlargement or elongation. Ordin (1958, 1960) found that turgor pressure was a more important factor in cell enlargement than the osmotic potential. A close relationship between decreasing turgor and decreasing enlargement of plant organs was found by Boyer (1965). This relationship is illustrated in Figure 1.11.

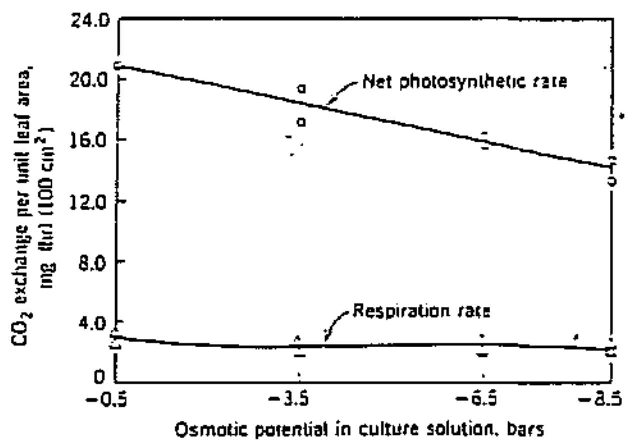


FIG. 1.10 Rates of photosynthesis and respiration of cotton plants growing in aquatic solutions of various osmotic potentials. The stomata remained open and the decrease in photosynthetic rate was therefore explained by protoplasmatic effects of the reduced water potential. From Boyer, 1965.

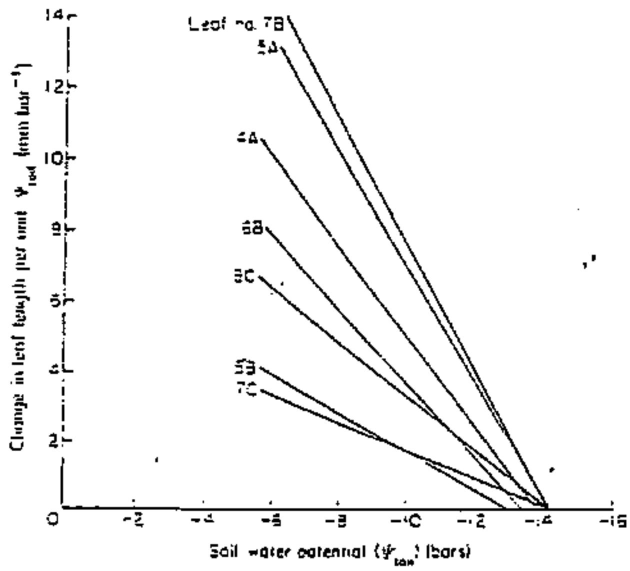


FIG. 1.11 Elongation rates of cotton leaves in relation to the soil water potential. The interception point indicates the value of the soil water potential at which growth stops. This value is close to the value at zero turgor pressure. From Wadleigh & Gauch, 1948.

Boyer (1968) found that growth was intimately linked with leaf water potential and with calculated turgor pressure. However, he had to estimate short term growth rate from the rate of water uptake by excised leaves. This made it impossible to detect temporary changes in growth related to rapid changes in plant water tissues.

Denmead & Shaw (1960) found that stem elongation of maize plants was reduced by water stress in the vegetative growth stage. The rate of stem elongation declined when the available soil water was depleted by more or less 75 %. Plants that were subjected to water stress were shorter than the well watered plants. The leaf area was smaller for all plants which had endured water stress while they were still increasing in size.

Hsiao, Acevedo & Henderson (1970) developed a method of measuring intact leaves on a minute to minute basis. They reported that leaf growth resumed immediately when a mildly water-stressed plant was watered again.

Acevedo, Hsiao & Henderson (1971) investigated immediate and subsequent growth responses of maize leaves to changes in water status. Leaf elongation was measured by a linear variable differential transformer. When the leaf elongates, a millivolt output proportional to the displacement is sent out and recorded. The soil water potential was measured with thin nylon Bouyoucus resistance units. They found that leaf elongation in maize responded immediately and was extremely sensitive to changes in plant water status. While a slight decrease in leaf water potential resulted in a slower growth, a raise of the leaf water potential caused a virtually instant growth acceleration. Similar results were found with wheat during experiments at Roodeplaat (Meyer & Green, 1980; Meyer & Green, 1981; Eastham, Oosterhuis & Walker, 1984). Recovery of the leaf water potential of maize leaves after rewatering versus time showed a more or less hyperbolic relationship (Boyer, 1968). Therefore, leaf water potential and turgor pressure of the leaf should be lower during the recovery period than in the subsequent steady state phase. Thus a higher elongation rate during the recovery period indicates that water stress increased the extensibility of the tissue. Acevedo et al. (1971) pointed out that if after rewatering growth of the leaves is faster than the well-watered plants, it is due to a slower growth of the leaves of the well-watered plants upon reaching maturity and not to an accelerated growth of previously stressed leaves. The truly rapid growth is very temporary and does therefore not contribute significantly to the total length of a leaf.

Hoogenboom, Peterson & Huck (1987) found that during drought periods the reduction in stem elongation and leaf area enlargement rates of soybean plants was significant. After rewatering an increase in stem elongation and leaf enlargement rates, in some cases higher than the rates of the well-watered plants, was observed. They found that if plants have experienced a short period of water stress, they showed optimal growth after rewatering and ended up comparable in size to the well-watered plants at the end of the season. They also pointed out that the adaptation that occurs during one stress period leaves a plant in a better condition to endure the next stress period.

Rosenthal, Arkin, Shouse & Jordan (1987) concluded that water deficits below 50% of the plant available water (PAW) reduced relative leaf extension rates. Water deficits below 20% to 30% of the PAW reduced transpiration, enhanced leaf senescence and increased leaf number.

Apart from leaf enlargement and shoot or stem elongation, the number of leaves or shoots may also be influenced by water deficits. Many agronomists (Fischer, 1973; Slatyer, 1973; Begg & Turner, 1976) have investigated the influence of timing and duration of soil water deficits on the morphological development of small cereal grains. However, much of their research was limited to the processes of inflorescence development and fertilization.

Research on the effects of water deficits on processes earlier in the vegetative stages pointed out that tillering can also be affected. Aspinall, Nicholls & May (1964) found a reduced tillering in barley after short periods of water stress. Upon rewatering a large transient increase in tiller development ensued and in some cases a larger maximum tiller population than in the well-watered plots was found. This tendency was greater the earlier stress was applied. A reduced tiller size and number of barley plants, caused by water stress during early vegetative growth was also reported by Lawlor, Day, Johnson, Legg & Parkinson (1981). In both cases, the effect of water stress on further development of the tillers and their yield was overlooked.

Cannel (1969) and Jones & Kirby (1977) pointed out that the time of tiller appearance of barley plants had a pronounced effect on yield potential and on water stress sensitivity respectively. Early formed tillers contributed most of the yield (Cannel, 1969). Barley genotypes which produce few large tillers having a high rate of survival gave relatively high yields in drought conditions (Jones & Kirby, 1977). Kirby & Jones (1977) found that late developing barley tillers compete with the main stem culm for plant nutrients without a significant contribution to yield, decreasing the yield potential of the main stem.

Rickman, Klepper & Peterson (1983) found that with a favourable soil water status, tiller development was earlier and less variable than it was under more stressful conditions. A delayed winter wheat tiller appearance, relative to normal development patterns, was found under adverse environmental conditions (Klepper, Rickman & Peterson, 1982).

Stark & Longley (1986) concluded that besides tiller appearance, also leaf area, tiller survival, tiller size, initiation of floral primordia, and the number of grains per spikelet can be affected by water stress (see also Oosterhuis & Cartwright, 1983). The time of tiller appearance is closely related to tiller survival, size, and productivity. Therefore, a delay of tiller development under water stress conditions will probably have a significant negative effect on yield potential.

Roots are normally hidden from view and therefore they have been neglected in most field studies of plant growth. However, there has been a significant increase in root research as investigators realized their important role in supplying water and nutrients to the plant (Arya, Blake & Farrell, 1975; Allmaras, Nelson & Voorhies, 1975; Botha & Bennie, 1983; Van Antwerpen, 1988).

A relationship between both total and relative root length and days after planting was found by Van Antwerpen (1988) with maize and wheat. His data showed that root length increased sharply during the vegetative growth stages until a maximum value was reached during the early productive stages. Thereafter, root length decreased due to root necrosis (see also Gerwitz & Page, 1974 and Taylor & Klepper, 1978).

As the roots are normally hidden from view, root growth is, therefore, difficult to monitor. The question arises whether there is a relationship between root growth and top growth. Erickson (1976), Botha, Bennie & Burger (1983) and Muller (1988) stated that there was a close relationship between root length index and leaf area index. Huck (1977) found a relationship between the quantity of roots and the number of leaves. Leaf area index was unfortunately not determined by Van Antwerpen (1988) but he believes (from visual observations) that a close relationship between root growth and top growth can be found.

Many factors such as soil texture, soil bulk density, mechanical resistance of the soil, chemical soil characteristics and soil water content have a big influence on root development (Barley, 1963; Taylor & Gardner, 1963; Camp & Lund, 1964; Taylor, Roberson & Parker, 1966; Barley & Greacen, 1967; Taylor & Ratliff, 1969; Lowry, Taylor & Huck, 1970; Payne, 1973; Bennie & Burger, 1979; Van Huyssteen & Van Zyl, 1981; Shierlaw & Alston, 1984; Bennie & Botha, 1986). A positive correlation between root growth and soil water potential was found for oats by Ehlers, Khosla, Kopke, Stulpnagel, Boehm & Baeumer (1980). However, Greacen & Oh (1972) stated that roots grow in wetter soil layers because of a lower mechanical resistance and not because of a higher soil water potential. Taylor & Gardner (1963) also found that the main factor for a decrease in root growth is the increased mechanical strength as the soil becomes drier. The relationships btween root growth and top growth found by Erikson (1976), Botha et al. (1983) and Muller (1988) were established from data collected from studies on plants under optimal growing conditions. Other researchers have demonstrated that water stress in the plant also has a definite influence on root growth.

Hoffman, Rawlins, Garber & Cullen (1971) found an increased mass ratio of root to shoot of cotton plants under mild to moderate water stress conditions. As the soil becomes drier, the water potential decreases and the soil's mechanical strength increases. Both processes cause a bigger resistance to root growth (Taylor & Gardner, 1963) and thus an increased relative root growth under mild stress conditions seems paradoxical. Hsiao (1973) explains this phenomenon by postulating that roots have a greater ability to adjust osmotically to water shortage than shoots. However, even with this ability for osmotical adjustment, root growth will slow down considerably and even stop when the soil becomes dry enough. The main factor for this seems to be the increased mechanical strength of the soil (Taylor & Gardner, 1963).

Hoogenboom, Huck & Peterson (1987) reported that during the early stages of vegetative development, the root growth of soybean plants was mainly limited to the upper regions in the soil profile. As the plants were growing, new roots were developing in the wetter parts of the soil. When water stress occurred, a major increase in root length was observed, especially in the deeper regions. This increase in root growth stopped upon rewatering. They concluded that during dry periods a greater portion of the photosynthetic assimilates was transported to the roots, favouring root growth, while during wetter periods the major part of the assimilates was transported to the shoots. However, during late-season drought this mechanism did not seem to work and plants with relatively small root systems were particularly susceptible to water stress injury (see also Huck, Ishihara, Peterson & Ushijima, 1983). Lang & Thorpe (1986) also reported that water potential differences within the plant affected the partitioning of the assimilates and found that regions with the highest potentials attracted most of the assimilates. If root growth increases as a result of water stress during the vegetative stages, then the maximum root length will be reached earlier in the season. The relationship between root growth and top growth is thus affected if water stress occurs during the vegetative growth stages and top growth indicators will give a false impression and underestimate the extensiveness of the root system. From this it seems that plants with a larger root system (developed during early vegetative growth stages, e.g. with a period of moderate water stress) would be better prepared for water stress during more critical stages later in the season.

1.2.3 The effect of plant water deficits on yield

The two most important processes related to the effects of water stress on yield are the production of photosynthetic assimilates and their distribution among the different plant parts (Hsiao et al., 1976). The effects of soil water stress on plants, their relations to yield and dependence of the growth stage at which water stress occurs are illustrated in Figure 1.12. The three parameters which determine the production of photosynthetic assimilates are total leaf area (source size), net assimilation per unit of surface (source intensity), and longetivity of the leaves (source duration). An additional parameter is the "sink size", introduced in case of a harvestable yield. The distribution of the assimilates is closely linked to this parameter. Neales & Incoll (1968) and Thorne & Koller (1974) reported that a reduction in sink size, causing an accumulation of assimilates, had a negative feedback effect on photosynthesis (source intensity). This relationship between sink size and source intensity is indicated by line 5 in Figure 1.12.

When water stress occurs during the reproductive stage, the partitioning of the assimilates will play an

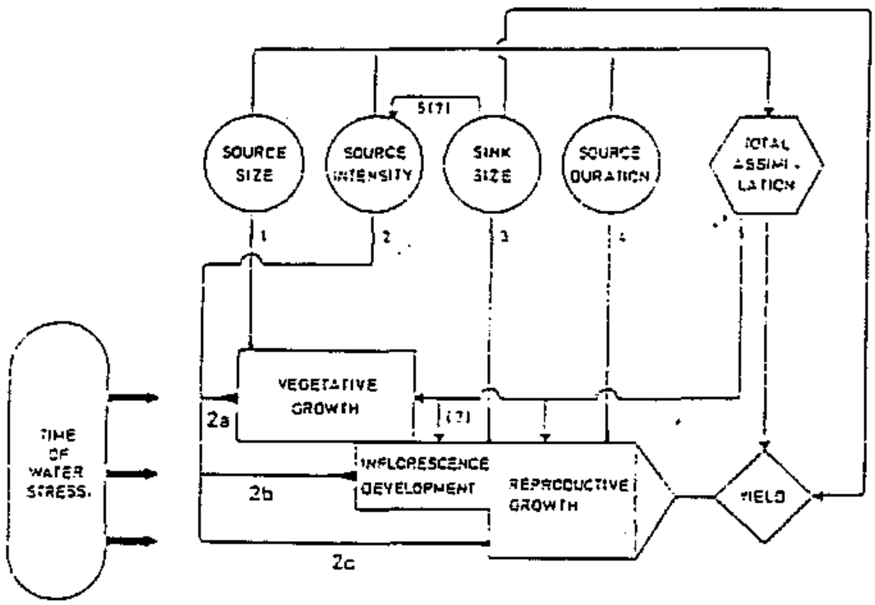


FIG. 1.12 Effects of water stress on yield. The effects vary with time and the cumulative effects would be the integrals over time. Arrows indicate negative effects and question marks represent effects that are not well established. From Hsiao et al., 1976.

important role in determining the final yield, especially when the yield consists of the reproductive organs of the plant. The size of the fruit sink will play an important role and thus the factors related to the fruit sink size: inflorescence development, fertilization, abortion of fertilized ovaries, and fruit abscission (Hsiao et al., 1976). The relationships between these factors and the final yield are outlined in Figure 1.13.

The effect of water stress on photosynthesis seems to play a smaller role in determining the final yield. Evans (1975) pointed out that for many plants, of which the yield consists of reproductive or storage organs, photosynthesis may not directly influence their yield.

These conclusions contradicted the views of Denmead & Shaw (1960). They ascribed the decrease in yield of maize on which water stress was imposed after ear development to a "reduced assimilation in the critical period when daily assimilation rates are high and when most of the assimilate is being used in grain production". This view is also supported by Boyer & McPherson (1975). They found that in maize about half of the dry matter accumulated by the shoot is ultimately transported into the grain and that partitioning of the assimilates was less sensitive than photosynthesis to water stress.

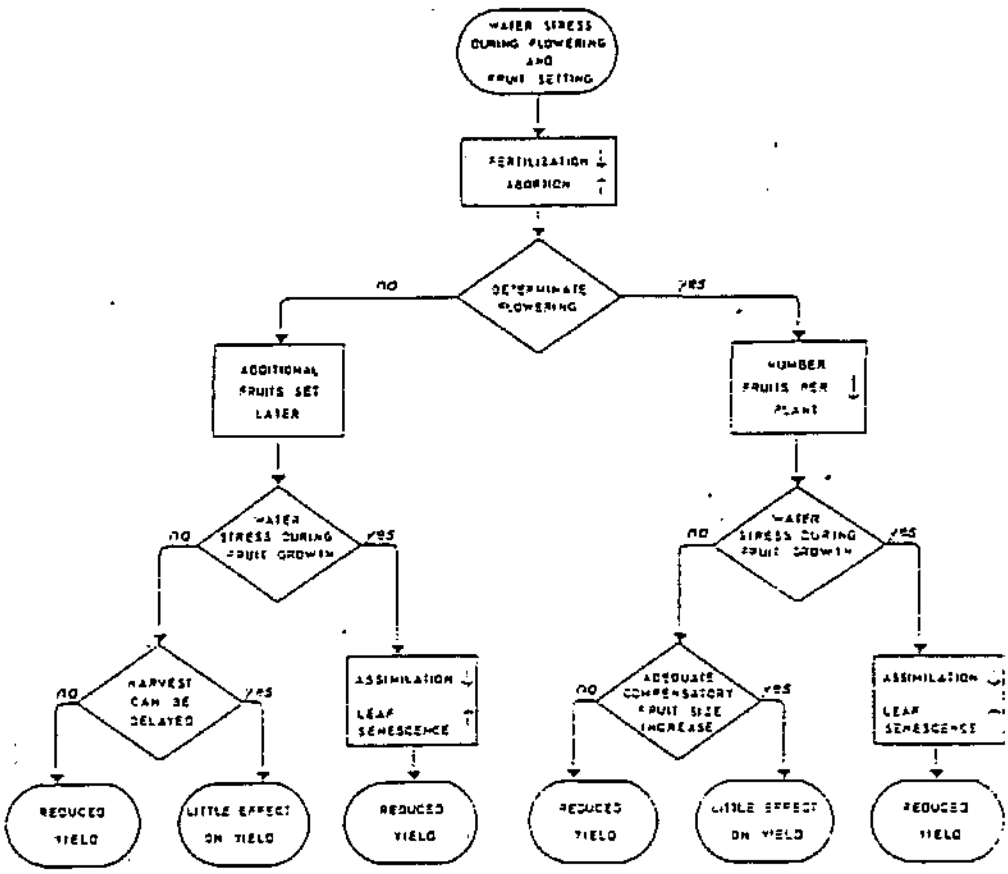


FIG. 1.13 Effects of water stress imposed during the reproductive stage. This diagram is based on data accumulated in the literature. The vertical arrows next to the variables indicate either an increase or a decrease of the variable. From Hsiao et al., 1976.

Denmead & Shaw (1960) reported reductions of 25%, 50%, and 21% in grain yield of maize caused by water stress during vegetative, silking, and ear stages respectively. These reductions in yield are comparible with those found by Robins & Domingo (1953). Eck (1986) found that water stress periods of two and four weeks during vegetative growth reduced the yield by 23% and 46% respectively. He also reported that the yield was reduced by 1,2% for each day of water stress during the grain filling stage. Eck concluded that a limited irrigation of maize is not a feasible practice, at least not on the Southern High Plains of the U.S.A. because water deficits reduced the yields and did not increase water use efficiencies.

The stage during which stress is imposed on the plants also plays an important role in determining the final yield. According to Frey (1982) the most critical period for yield determination in the life cycle of maize begins approximately two weeks before silking and continues until two to three weeks after silking. Shaw (1974) reduced this period to five days before silking until five days after silking but stated that this period is followed by a period of four weeks that is less crucial and relatively constant in sensitivity to stress. Stress during vegetative growth stages seems to be less damaging than during pollination or grain filling stages (Robins & Domingo, 1953; Classen & Shaw, 1970). Tollenaar (1977) found that severe stress before silking resulted in a poor ear development and in some cases in no ear development, while stress after pollination limited the number of grains.

Eck (1986) studied the effects of water deficits, imposed during the vegetative stages, on the yield of maize. He found that when stress was induced during early or late vegetative growth, the yield was reduced. Water deficits in the early vegetative stage reduced leaf area, stalk height, and final yield while stress imposed in the late vegetative stage reduced stalk height and final yield and had no effect on the leaf area. Eck also reported that the reduction in the seed numbers as a result of water deficits during the late vegetative stage were similar to those resulting from deficits during the early vegetative stages. This supports the theory of Hanway (1966) which states that the yield potential is already determined during the vegetative period.

1.3 GENERAL BACKGROUND TO THE PRESENT STUDY

1.3.1 Review of PAWC research at the University of Fort Hare

During the period 1976 to 1981 a research project was conducted in the Department of Soil Science at the University of Fort Hare with the objective to determine the profile available water capacity (PAWC) for different [crop-soil-evaporative demand] systems under irrigation, aiming at promoting the optimum use of irrigation water (Hensley & De Jager, 1982). They defined "profile available water capacity" for a specific crop and soil under a certain evaporative demand as "the amount of water which is held in the effective root zone between field capacity and first material stress". The lower limit of PAWC (first material stress) was defined as: "the quantity of water in the soil profile at the degree of crop water stress at which the next irrigation should be applied if optimum yield is to be obtained". This definition was later changed to: "First material stress can be defined as the soil water content at which plant physiological processes have been reduced by 25% of their normal rate" (Hensley, 1984). They defined field capacity (upper limit of PAWC) as the amount of water retained in a soil profile when free drainage has materially ceased.

The techniques used to detect first material stress were visual symptoms, leaf diffusive resistance, leaf water potential and the ratio of actual evapotranspiration to pan evaporation. No parameters directly linked to plant performance such as growth or yield were used. Because the use of these parameters will probably lead to a very accurate definition of the lower limit of PAWC, they were extensively used in the present study.

The concept of PAWC as defined by Hensley & De Jager was tested out for several crops at full canopy development on a variety of soils and reproducable results were obtained. From their data Laker (1982) compiled a first simple equation to predict the PAWC for different irrigated [soil-evaporative demand] systems for maize. This led to a follow-up project with the aim of developing PAWC models.

The development of PAWC models was studied by Boedt and Laker in a research project in the Department of Soil Science at the University of Fort Hare (Boedt & Laker, 1985). Their research consisted of the determination of PAWC for a selection of important crops on a variety of soils under different evaporative demands in the Ciskei and at the Vaalharts and Loskop irrigation schemes. They experienced problems with the interpretation of pre-dawn leaf water potential as a parameter to indicate first material stress in crops under very high evaporative demand. Visual symptoms as described by Mallett & De Jager (1971) and Hensley & De Jager (1982) could also not be used since plants wilted fairly early in the morning even in soils at field capacity under these conditions. Eventually Boedt & Laker (1985) resorted to the use of early morning wilting (at 09h00) as indicator of first material stress. Again this emphasizes the importance of the use of parameters which are directly linked to plant performance. The obtained results were used to compile equations to estimate the PAWC and the profile extractable water (PEW), i.e. the maximum amount of water that can be extracted from the soil profile by a specific crop without causing significant yield reductions (Boedt & Laker, 1985), for maize and wheat using the physical and chemical properties of the soils combined with the effective rooting depth and the depth at which specific pedogenetic horizons occur.

Irrigation scheduling experiments were carried out in order to test the PAWC concept. The effect of irrigation, at extraction of different fractions of PAWC, on seasonal water use, yield and water use efficiency was studied.

Boedt & Laker (1985) concluded that the PAWC concept seemed to provide a consistent basis on which to base irrigation scheduling. The results showed that past a certain threshold value of extracted water yields dropped to economically unacceptable levels and hence indicated the necessity to improve identification of the lower limit of PAWC. This could possibly be done by comparing plant performance related parameters with the previously used pre-dawn leaf water potential and wilting parameters.

Finally, deficit irrigation was superficially studied and some promising results were found (Boedt & Laker, 1985). Further research in this field was therefore highly recommended.

1.3.2 Objectives of the present study

Until now PAWC determinations and related studies have always been conducted at the full canopy phase or flowering stage (Hensley & De Jager, 1982; Boedt & Laker, 1985). A need still existed for studying PAWC at different young growth stages and its evolution as plants grow towards maturity. This was, therefore, the first objective of the present study.

A second objective was to improve identification of first material stress, the lower limit of PAWC, in view of the unsatisfactory results found by Boedt & Laker (1985) with pre-dawn leaf water potentials and visual symptoms under conditions of high evaporative demand. It was also aimed to find an explanation for the fluctuating pre-dawn leaf water potential patterns found by Boedt & Laker (1985) under these conditions.

The third objective was to determine the relative sensitivity of a few major crops to soil water stress at different growth stages, both in terms of vegetative growth and yield, in order to adapt irrigation scheduling so as to avoid soil induced water stress during the most sensitive periods.

The fourth objective was to study the effects of different deficit irrigation patterns on yield and water use efficiencies, in order to identify the most efficient irrigation scheduling strategy.

1.3.3 Broad outline of the present study

The characteristics of the experimental sites and the research techniques are described in Chapter 2. Special attention was given to the pre-dawn leaf water potential measurement technique for which a standardized method was described. Leaf expansion measurements led to further research into the relationship between leaf length and leaf area index. A complete statistical analysis of this relationship is also given in Chapter 2.

A study of PAWC at different growth stages was conducted at three sites. This research involved leaf expansion measurements (maize), stem elongation measurements (maize, wheat and durum wheat) and yield determinations (maize, wheat and durum wheat). The results of these measurements were compared with pre-dawn leaf water potential readings to detect first material stress and they were also used to define the degrees of sensitivity of the crop to soil water stress. Three short, intensive ecophysiological studies were undertaken with maize in an attempt to improve identification of the lower limit of PAWC and to find explanations for the fluctuating pre-dawn leaf water potential patterns previously found. These studies included diurnal measurements of leaf water potentials, net carbon-dioxide exchange rates and stomatal conductances. An irrigation scheduling experiment with maize aimed at defining the sensitivity to soil water stress at different growth stages was conducted at site ISO. During this experiment an intensive study was done on leaf expansion and stem elongation in maize. These facets of the study are extensively discussed in Chapter 3.

The irrigation scheduling experiments with wheat, durum wheat and maize are discussed in Chapter 4. Different irrigation treatments, with the emphasis on deficit irrigation, were applied and seasonal water use, yield and water use efficiencies were determined.

Studies on miscellaneous aspects related to the PAWC research are discussed in Chapter 5. These studies include a simple method to delineate filled up gullies (dongas), the relationships between salt content, yield and irrigation regime, the influence of heavy irrigation combined with gypsum applications on the leaching of soluble salts at site ISO-A, the determination of drainage curves for the soils at all four sites and information regarding root densities at different depths.

Conclusions and some recommendations for future research and practical on-farm applications of the results of the present study are given in Chapter 6.

CHAPTER 2

DESCRIPTION OF EXPERIMENTAL SITES AND GENERAL RESEARCH TECHNIQUES

2.1 INTRODUCTION

The research was conducted at the Cradock Experimental Station of the Department of Agriculture and Water Supply near Cradock in the Eastern Cape Province, Republic of South Africa. Cradock (32° 08´ S, 25° 37´ E; 660 meter above sea level) is situated about 250 km north of Port Elizabeth at the eastern border of the Great Karoo, a large semi-arid region in the central part of South Africa.

There were several reasons for selecting the Cradock Experimental Station as venue for this research project. The most important ones are:

1. The research of Boedt & Laker (1985) left some

unresolved questions regarding soil-plant-water relationships under conditions of high evaporative demand. This research, therefore, had to be conducted in an area with hot, dry summers. Since Cradock is in a semi-arid area with hot summers, it was expected that it would be well-suited for this project. Being a semi-arid area it was also anticipated that rainfall interference with the research would be minimal.

2. The Cradock Experimental Station is situated in the Fish River valley, where intensive irrigation is practiced. Major irrigation expansion is expected in this region, but little or no basic irrigation research has been done here - especially in regard to soil-plant-water relationships. The Cradock Experimental Station is climatologically and pedologically representative of the area.

3. The Cradock Experimental Station has good infra-structure for irrigation research.

4. The Cradock Experimental Station is situated only 160 km from the University of Fort Hare, making it possible for the project leader to maintain a fair degree of contact with the researcher between his lecturing and administrative duties at the University.

2.2 CLIMATE

Cradock has an average annual rainfall of 341 mm with maximal falls in February and March (late summer to early autumn). An estimate of the annual potential evapotranspiration (PET) was determined by means of the long term average Class A evaporating pan data in Table 2.1. and a value of 2370mm was found (Arnon, 1972). Because water supply is limited the actual evapotranspiration (AET) is much lower (Thornthwaite, 1948). The average monthly AET at Cradock was calculated according to an amended version of the Thornthwaite & Mather (1957) equation (Figure 2.1). The annual AET was found to be 817mm. The Thornthwaite water budget shows a deficit throughout the year, with the biggest deficits during the mid-summer months of December and January (Figure 2.1). This is the time of year during which the water requirements of summer crops are the highest and also when the plants are the most vulnerable to water stress (flowering period for most summer crops). Long term average climatic data for Cradock are listed in Table 2.1.

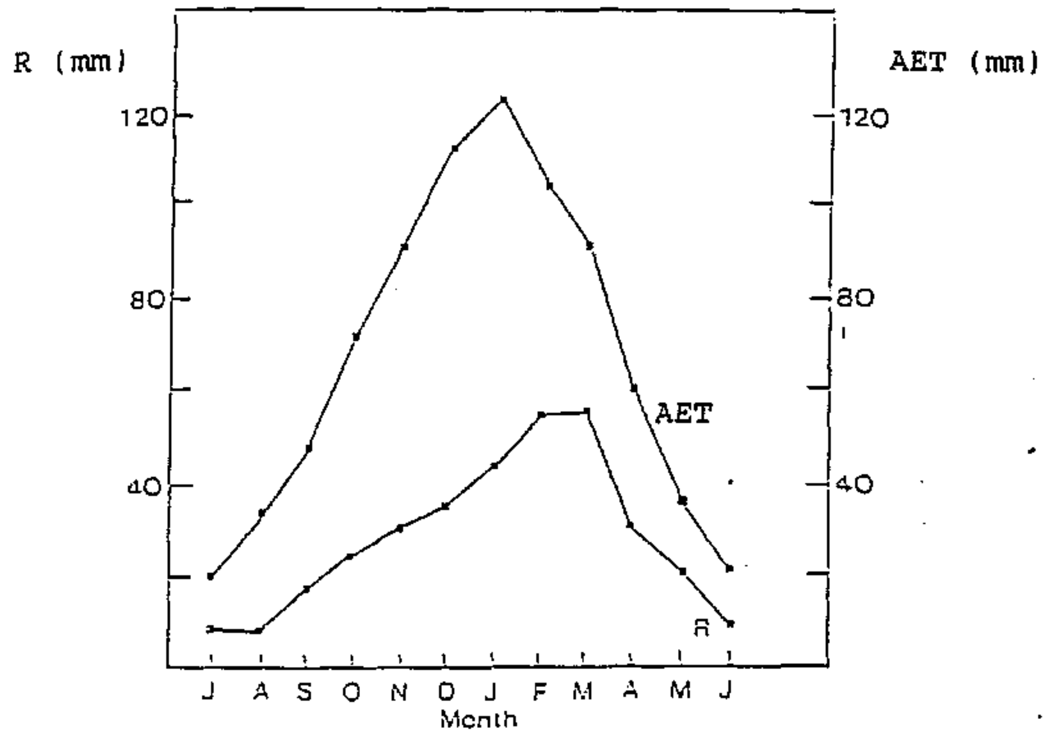


FIG. 2.1 Average monthly actual evapotranspiration (AET) and rainfall (R) at Cradock. AET calculated by M. Austen, Dept. of Crop Science, University of Fort Hare, according to an amended version of the Thornthwaite & Mather (1957) equation based upon local data for the Eastern Cape.

The winter months, June and July, are characterized by average maximum temperatures below 20°C, average minimum temperatures below 5°C, low windspeeds and low rainfall. Frost during the nights is very common during these months. Although the temperatures rise quickly from August onwards, frost can still be experienced during September and sporadically during October. The windspeed starts increasing during August and reaches maximum values during December, January and February. These months also show the highest evaporation figures as a result of the high temperatures and frequent hot winds. Although the highest rainfall is normally expected during February and March (Table 2.1), rainfall in the area is very erratic as indicated by the data for the research period (Table 2.2).

TABLE - 2.1 Long term average climatic data for Cradock.

Month	maxT (°C)	minT (°C)	aveT (°C)	rain (mm)	evap (mm)	wind (km/d)
Jan	30,8	14,3	22,6	42,4	304,2	257,2
Feb	30,2	14,8	22,5	57,4	231,0	225,8
March	28,0	12,8	20,4	51,6	204,9	186,4
April	24,9	9,5	17,3	30,2	150,6	149,8
May	21,2	5,3	13,4	20,6	123,8	152,1
June	18,5	3,1	11,0	10,4	104,1	154,0
July	18,4	2,3	10,5	19,6	116,3	158,6
Aug	20,6	3,6	11,9	13,6	152,7	183,1
Sept	23,3	6,3	14,6	12,4	185,3	208,1
Oct	25,5	8,8	17,1	37,0	231,3	224,3
Nov	27,4	11,0	19,3	30,6	263,1	243,0
Dec	29,8	12,9	21,3	41,8	303,0	251,9

TABLE 2.2 - Climatological data for the duration of the research project at the Cradock Experimental Station.

Month	average maxT(°C)	average minT(°C)	average T(°C)	total rain(mm)	total evap(mm)	average wind(km/d)
1985						
June	20,3	3,3	11,8	8,6	102,0	133,3
July	19,3	2,6	11,0	2,5	108,0	124,8
Aug	23,9	7,2	14,7	0,0	192,5	181,2
Sep	24,5	7,2	15,0	5,5	195,0	179,9
Oct	26,6	10,9	18,8	56,5	174,5	206,4
Nov	27,9	13,7	20,8	86,5	192,0	208,0
Dec	27,1	13,1	20,1	168,5	169,5	199,5
1986						
Jan	30,4	14,5	22,5	29,5	248,5	230,2
Feb	30,0	13,5	21,8	36,6	211,5	228,0
March	28,8	12,3	20,6	53,2	172,5	181,9
April	26,6	10,0	18,3	12,5	142,5	155,5
May	24,8	6,2	15,5	0,0	151,0	133,6
June	19,8	4,1	11,9	12,0	122,0	167,6
July	19,8	2,0	10,9	0,0	112,5	143,9
Aug	20,7	4,4	12,5	11,6	125,6	155,1
Sept	24,5	6,9	15,7	1,0	210,5	216,5
Oct	24,9	10,8	17,8	69,5	187,5	251,2
Nov	26,9	10,8	18,9	40,0	247,5	225,2
Dec	30,8	13,3	22,1	13,5	330,0	298,9
1987						
Jan	31,3	14,2	22,8	30,8	319,3	286,5
Feb	32,4	16,0	24,2	52,1	240,6	237,4
March	29,0	13,6	21,3	7,8	215,3	218,0
April	26,8	10,4	18,6	22,8	156,3	168,1
May	25,0	7,2	16,1	25,4	137,0	141,2
June	18,0	3,6	10,8	20,5	87,8	159,9
July	18,8	2,1	10,5	21,5	91,0	137,5
Aug	21,0	4,8	12,9	5,3	139,3	202,6
Sep	21,1	7,5	14,3	70,5	126,7	251,7
Oct	25,7	9,7	17,7	5,0	206,0	210,5
Nov	27,8	12,2	20,0	59,1	235,1	256.2
Dec	31,2	13,4	22,3	12,8	282,8	239,4
1988						
Jan	30,7	14,3	22,5	26,6	284,1	261,6
Feb	30,3	15,7	23,0	120,9	200,4	202,7
March	28,4	15,0	21,7	26,1	160,2	151,6
April	22,3	8,1	15,2	40,1	116,6	127,5
May	22,5	6,4	14,4	9,3	121,5	123,2

During the duration of this project temperatures and potential evapotranspiration in general did not reach the extremes experienced at Vaalharts by Boedt & Laker (1985). For short, critical periods evaporative demands did reach adequate intensities to facilitate explanation of certain effects found during the Boedt & Laker study (Laker et al., 1988). A complicating factor at Cradock was the dew which formed on leaves during many nights, making pre-dawn leaf water potential determinations and other early morning plant physiological studies difficult.

2.3 SOILS

Four sites representing some of the dominant irrigated soil types in the Fish River valley were selected. The sites were named as follows: D6, D12, D16 and ISO. Sites D6, D12 and D16 were close to each other on the lowest and youngest alluvial terrace of the Fish River. Site ISO was on a higher, older terrace. Detailed profile descriptions and analytical data for the soils of the four sites are given in Appendices 2.1.1 to 2.1.4.

The soils at all four sites are young soils of alluvial origin. Typically of such soils the spatial variability at all sites is extremely high. This is a far from ideal situation for research purposes (but does represent the real situation for most irrigated soils on alluvial terraces in these semi-arid regions).

According to the South African binomial soil classification system (MacVicar, De Villiers, Loxton, Verster, Lambrechts, Merryweather, Le Roux, Van Rooyen & Harmse, 1977) the soils are classified as follows:

Site name	Soil classification	
	Form	Series
D6	Oakleaf	Limpopo
D12	Oakleaf	Limpopo
D16	Dundee	Dundee
ISO	Oakleaf	Allanridge

The soil classification according to Soil Taxonomy (USDA, 1975) is given in Appendices 2.1.1 to 2.1.4.

The clay contents of the soils vary from low (<10%) to moderately high (>30%). All the soils are characterized by high to very high silt contents and very high fine sand contents. The soils consist almost entirely of particles smaller than 0,25mm in diameter, actual figures for the <0,25mm fraction ranging from 95 to 99%. It is well known that due to the high silt and fine sand contents of the alluvial and colluvial soils derived from Beaufort sediments in the Eastern Cape, Ciskei and Southern Transkei, these soils are exceptionally prone to crusting and sub-surface compaction.

Strong crusting did occur in the experimental plots of the present study and special measures had to be taken to overcome its detrimental effects, especially on seedling emergence. These measures included gypsum applications before planting and light irrigations about one week after planting (in order to soften the crust during the period of seedling emergence).

Because of the extremely high silt and fine sand contents of the soils, subsoil compaction could be a factor limiting root growth and thus reducing PAWC. The latter was unexpectedly found not to be the case, as will be shown in Chapter 3. The bulk densities at different soil depths are listed in Table 2.3. The values measured at site D6 were fairly high, especially at depths between 700 and 1000mm. The detrimental effect of soil compaction in this part of the profile on root growth is clearly illustrated in the soil water extraction patterns which are discussed in Chapter 3. The rest of the bulk density values are relatively low compared to values generally found on the central irrigation schemes, e.g. Vaalharts (see, for example, Van Antwerpen, 1988).

TABLE 2.3 - Bulk densities at different soil depths for the soils at the five sites.

Depth (mm)	Bulk density (kg per cubic meter)			
	D6	D12	D16	ISO
150	1460	1470	1500	1530
300	1520	1500	1460	1530
450	1570	1430	1440	1570
600	1520	1440	1480	1550
750	1710	1410	1510	1560
900	1630	1390	1490	1550
1050	1520	1370	1480	1630
1200	1490	1370	1580	1580
1350	1570		1590	1600
1500	1570		1610	1590

All the soils are calcareous - a result of the poor leaching due to the low rainfall and high PET. The soils also contain some soluble salts and significant quantities of exchangeable sodium, but not enough to classify them as saline or sodic. In some plots at site ISO it was high enough to affect yields adversely, as will be pointed out later. The pH (water) of the soils was also high, ranging from 8,1 at site D6 to 9,0 at site ISO. This problem was alleviated by gypsum applications followed by an immediate irrigation two weeks before planting.

The irrigation scheduling experiments were all conducted at site ISO. This is because this site had an elevated irrigation furrow from which a large number of 50 square meter plots could be irrigated quickly and easily. A second furrow was constructed for the purpose of the project. The area around the old furrow had been cultivated for some time and some plots had been affected by salinity, possibly due to leakage from a nearby cement dam. The area around the new furrow was virgin land before the experiments started and did not have as much variation as the former. This must be kept in mind when comparing results from different seasons since some experiments were done on the old area (ISO-A) and some on the adjacent new area (ISO-B). The two areas were never combined in a single experiment.

Finally, the sites were situated as far as possible from other irrigated fields in order to minimize the influence of irrigations applied by other researchers.

2.4 GENERAL RESEARCH TECHNIQUES

2.4.1 Layout of the experiments

Five plots of 5m by 5m were layed out at each of sites D6, D12 and D16 for experiments during young growth stages (Figure 2.2). At site ISO 28 plots of 10m by 5m were layed out at ISO-A (respectively 16 plots and 12 plots on each side of the furrow) and 32 plots of the same size were layed out at ISO-B (16 on each side of the furrow). A ground plan of the plots at site ISO is given in Chapter 4. Border areas were always planted around the plots to reduce oasis effects.

An aluminium neutron hydroprobe access tube was inserted in each plot to a depth of 1500mm. The bottoms of the tubes were sealed by means of welded aluminium plugs to prevent water from entering the tubes. The upper ends of the tubes were 150mm above ground level to prevent irrigation water from flowing in. The tops of the access tubes were covered with overturned tin cans to prevent the entry of rain water and small animals.

At harvest only a central area of 3m by 3m (sites D6, D12 and D16) or 8m by 3m (site ISO) was sampled for yield

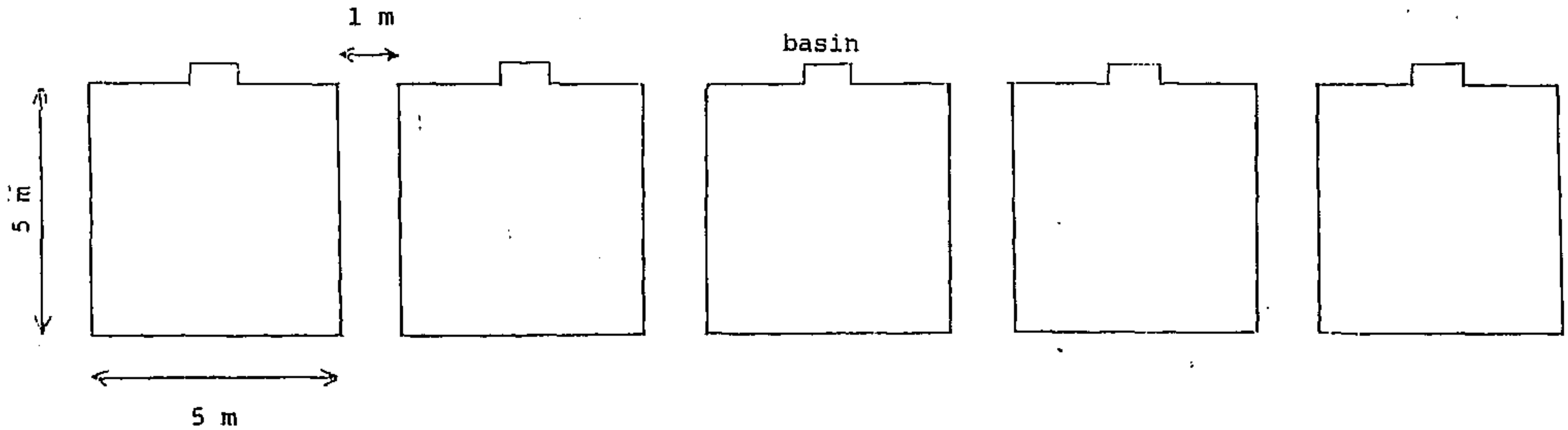


Fig. 2.2 Ground plan of plots at sites D6, D12 and D16.

determination purposes. This was done to minimize the effect of different treatments in adjacent plots.

2.4.2 Protection against animals and rain

A fence of strong netting was erected around the plots at sites D6, D12 and D16 to protect the plants against rabbits, especially during the early vegetative stages. At site ISO an electrical fence was erected for the same purpose. Combined with manual rabbit control these measures reduced damage by rabbits to insignificant levels.

More important was the protection against rain during the drying cycles. Before the start of the drying cycles, rainsheds were constructed over the plots at sites D6, D12 and D16. The size and the number of the plots at site ISO made the covering of the area impossible, and only in the case of maize could the plots be protected against rain. The types of rain sheds were very different for wheat and maize.

In the case of wheat and durum wheat a wooden construction was built on each plot (Figure 2.3). As it started to rain a uvidek plastic sheet was rolled over

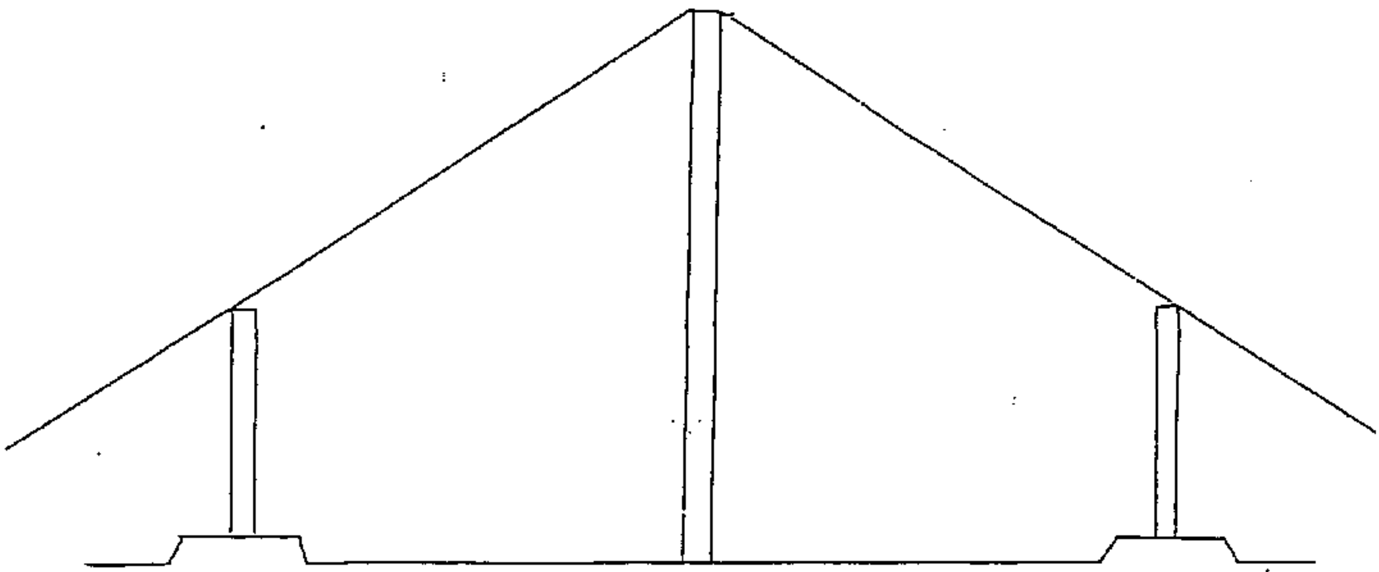


Fig. 2.3 Construction for protection against rain (for wheat and durum wheat).

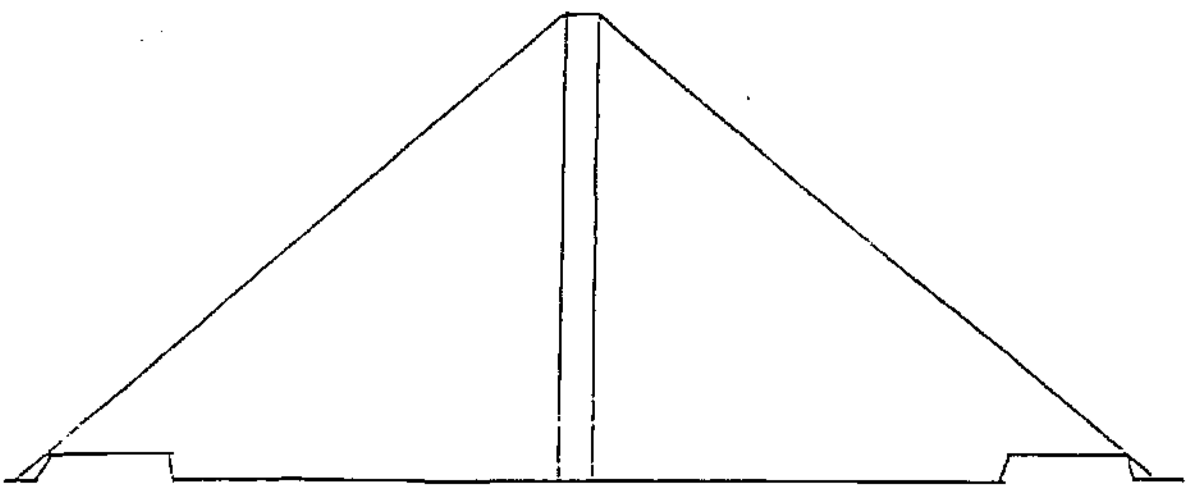


Fig. 2.4 Type of construction for protection against rain used during this study (for wheat and durum wheat).

the wooden framework, leaving the sides of the shed open to allow for a good aeration. Next to the plots a small ditch on either side collected the water which ran off the plastic covers and prevented it from running into the plots. The plastic cover was high enough to prevent the crop from touching the plastic and to allow a free movement of air under the plastic cover. In previous research the latter was found to be very important (Boedt & Laker, 1985). However, this type of construction proved to be very vulnerable to strong winds. It was then decided to build an alternative type of construction as illustrated in Figure 2.4. These rain sheds were much stronger and less susceptible to strong winds. The only negative aspect of these rain sheds was that the plastic damaged the plants in the border rows. However, this was only a minor disadvantage as the border rows were not used either for the experiments or for yield determinations.

On the plots with maize no constructions could be built that were high enough to cover the plants and leave space for a free movement of air. The soil between the rows was covered with strips of uvidek plastic sheet. The borders of the strips formed a small ridge which leaned against the stem of the plants and the adjoining plastics were secured with staples. The wall around the plot was

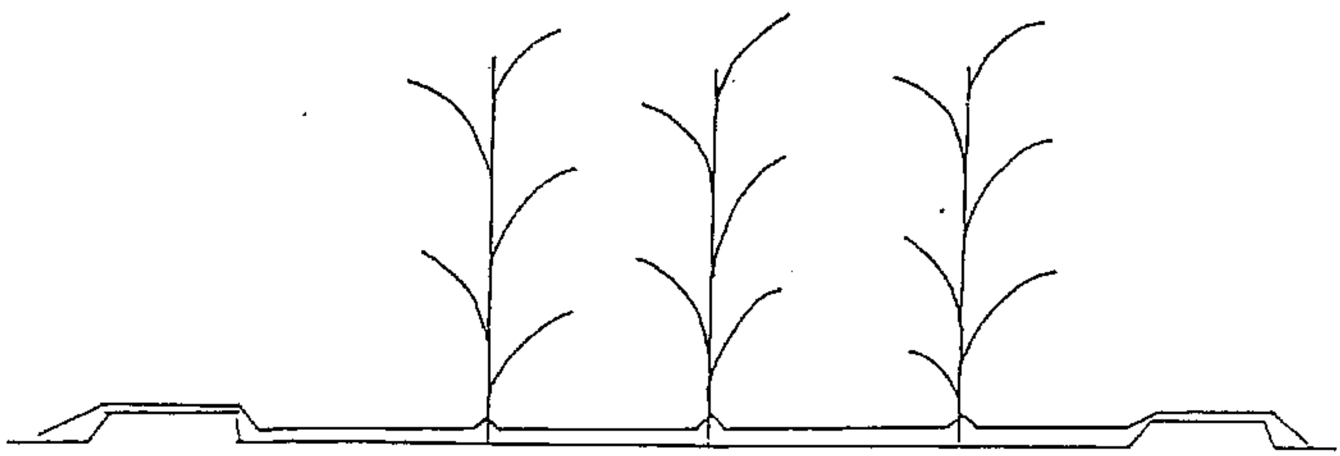


Fig. 2.5 Rainshield used on plots with maize.

removed on one side to allow for a free run-off of the rain water. Once the plastics were placed in position they were not removed until the end of the drying cycle. This type of rain shield is illustrated in Figure 2.5. A similar technique was used by Boedt & Laker (1985) for maize.

2.4.3 Irrigation techniques

Flood irrigation was used in all experiments. At sites D6, D12 and D16 the plots were irrigated by means of a pump. The pump was calibrated at regular intervals to ensure that the correct amount of water was applied. At site ISO the plots were irrigated directly out of a specially designed furrow. The water flow out of the furrow was calibrated and four plots could receive 75 mm in a time period of six minutes.

All plots were levelled before planting to ensure an even distribution of water. To prevent soil erosion a block of concrete was put on the spot where the water dropped out of the furrow in the plots at site ISO. At sites D6, D12 and D16 soil erosion was prevented by putting the end of the pipe in a small basin out of which the water flowed more gently into the plots.

2.4.4 Agronomic practices

The cultivars, fertilizer applications, planting densities and pest and weed control treatments were recommended by the local researcher Mr. J. Pretorius at the Cradock Research Station. Detailed agronomic practices for every season at all sites are given in Appendices 2.2.1 to 2.2.11. The size of the plots was too small for mechanical planting and therefore planting was done by hand.

The original cultivars were Zaragossa for wheat, Fargo for durum wheat and Pioneer PNR 542 for maize. After the first winter season the wheat and durum cultivars were changed to Gamtoos and Moni respectively because the original cultivars became susceptible to rust infestation. During the 1987-1988 summer season the maize cultivar was changed to Pioneer PNR 6528 as the other cultivar was no longer available.

Fertilizer applications were different every season as they were determined by the chemical analyses of the soil (Appendices 2.2.1 to 2.2.11).

Before and after the experiments regular irrigations kept the soil water content at a high level except where drying cycles were prolonged after first material stress (FMS) was detected. The experiments on all plots were started with soils at field capacity. All plots were irrigated just before flowering in order to eliminate stress effects during this very sensitive period. In a few cases plants were stressed during this period in order to measure the magnitude of the effect of water stress during this period.

2.4.5 General measuring techniques

2.4.5.1 Soil water content measurements

All soil water measurements were done by means of a Campbell Pacific Nuclear neutron hydroprobe (model CPN 503). The instrument was calibrated against different soil water contents determined gravimetrically at depth intervals of 150 mm up to a depth of 1500 mm for each soil.

Field capacity values were determined at all sites. A small plot was irrigated several times to ensure a complete wetting of the profile. An aluminium neutron probe access tube was inserted into the soil and the soil surface was covered with a plastic sheet to prevent evaporation. Readings were taken on a regular basis and when drainage had effectively stopped, the measured volumetric soil water contents were taken as the field capacity values.

In each plot two neutron hydroprobe access tubes were inserted into the soil and the soil water content was monitored constantly. A new technique for taking standard counts with the neutron hydroprobe was used towards the end of the study. The probe was put on an aluminium access tube at about 1,5m above ground level. This technique was suggested by Reginato & Nakayama (1987) and provided better results than with the probe on the box, as is the general recommendation. A major advantage was the more consistent standard readings due to less interference of the water in the soil and the surrounding vegetation (mainly grasses). Standard counts were taken daily before and after soil water measurements and their average value was used to calculate the count ratios which are used in the calibration formulas. When many measurements had to be done, standard counts were also taken between some readings. These counts were not used in the calculations but were merely a check to ensure that the hydroprobe was still functioning correctly. Neutron hydroprobe readings were taken at 150 mm depth intervals starting at a depth of 150 mm up to a depth of

1500 mm.

2.4.5.2 Leaf water potential measurements

The pre-dawn leaf water potential (PLWP) was selected as the indicator for first material stress (FMS). PLWP measurements were done by means of a pressure chamber similar to the one described by Scholander, Hammel, Hemmingsen & Bradstreet (1964).

The method of sampling, as well as the measuring itself and the sequence of measuring were done according to a standardized procedure in order to obtain representative and reproducible values.

Sampling of the leaves started about 20 to 30 minutes before sunrise, depending on the number of samples to be taken. The leaf on which the readings were done was the youngest, completely developed leaf (the flag leaf in the case of wheat and durum wheat at flowering stage). The importance of selecting mature leaves was illustrated during the experiments with durum wheat at young growth stages. The values of immature leaves were constantly lower than those of mature leaves and indicated FMS incorrectly (Chapter 3). The leaf was cut off the plant and put in a plastic bag labelled with the plot number. The bags were initially lined with aluminium foil. However, the foil was very fragile and since tests had proved that the foil did not have any influence on the measured values the foil linings were subsequently omitted.

During the drying cycles, PLWP measurements were done on a daily basis. For wheat and durum wheat five leaves were sampled and one reading was done on each leaf. The average of the five readings was taken as the PLWP value. In the case of maize, three leaves were sampled and two of the leaves were measured twice. The average of the five readings was taken as the value for that day.

The measuring techniques were slightly different for wheat and maize. In the case of wheat and durum wheat, the leaf was cut in half and the upper half was placed in the pressure chamber with the cut on top. The cut was studied with a magnifying glass (x10) while the pressure in the chamber gently increased. As soon as bubbles started forming on the cut surface, the value of the pressure in the chamber was noted and its negative value was taken as the leaf water potential. In the case of maize, a small piece (50 mm long and 10mm wide) was cut out of the middle of the sampled leaf as close as possible to the main vein. The cut closest to the tip of the leaf was studied with a magnifying glass (x10). The PLWP value was obtained in the same way as for wheat.

Pressure chamber measurements commenced virtually immediately after sampling was completed each morning. Although sampling was done very quickly, taking only 10 to 20 minutes to complete (depending on the number of samples collected), and measurements were also completed within a time space of 15 to 45 minutes from the first measurement (depending on the number of samples), there could be some concern regarding possible effects of differential time lapses between sampling and measurement on the PLWP values obtained.

In order to reduce possible time-lapse effects, PLWP measurements were not done in the same sequence as the sampling was done. A "semi-cyclical" measurement sequence was used and a close check was kept on possible consistent trends in differences between cycles. This semi-cyclical measurement sequence can be summarized as follows:

Step 1: Measure the first three leaves of the first plot sampled at the first site.

Step 2: Measure the first three leaves sampled on the first plot at each subsequent site.

Step 3: Measure the first three leaves sampled on the second plot at each site, starting with the first site sampled. Then do this for the third plots, and then for the fourth plots, etc.

Step 4: Hereafter repeat steps 1 to 3 for the 4th and 5th leaves (wheat) or 1st and 2nd (maize) sampled on each plot.

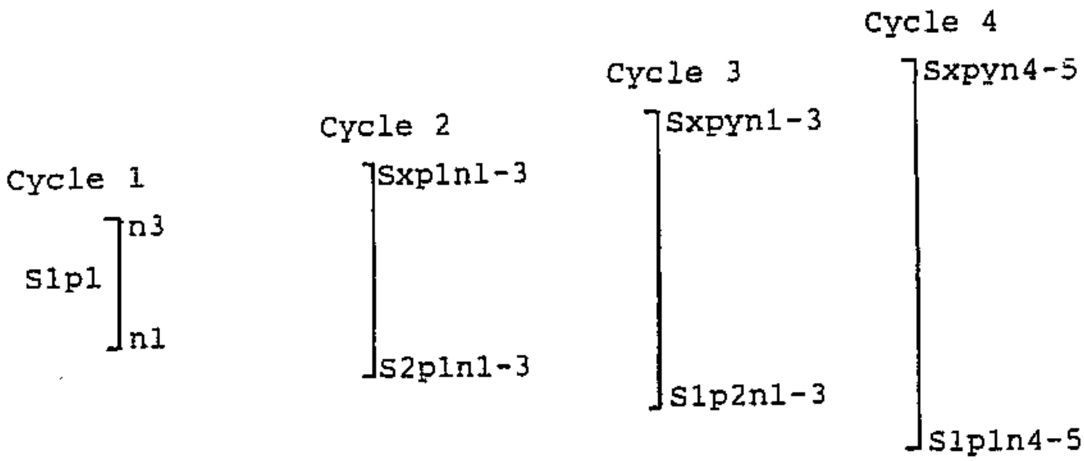
This measuring sequence is diagrammatically illustrated in Figure 2.6.

It was found that within the time frames between first sampling and last measurement, the time lapsed between sampling and measurement did not affect the values obtained. This is clearly illustrated by the two examples given in Table 2.4.

Table 2.4 - PLWP (ψpd) values of maize measured according to the semi-cyclical sequence.

Day	Plot	ψpd values (-kPa) 1	2	3	4	5
1	D6a	100(1)	150(2)	150(3)	100(13)	100(14)
	D12a	150(4)	100(5)	150(6)	100(15)	150(16)
	D6b	200(7)	200(8)	150(9)	200(17)	150(18)
	D12b	150(10)	100(11)	150(12)	200(19)	100(20)
6	D6a	200(1)	250(2)	200(3)	250(13)	250(14)
	D12a	150(4)	200(5)	150(6)	150(15)	200(16)
	D6b	250(7)	300(8)	200(9)	250(17)	300(18)
	D12b	200(10)	250(11)	200(12)	200(19)	250(20)

Sampling sequence on each day: D6a 1-5; D6b 1-5; D12a 1-5; D12b 1-5.
Measuring sequence on each day given in brackets.



S = sites (S1 = Site 1, i.e. first site sampled)

p = plot (p1 = plot 1, i.e. first plot sampled at a specific site)

n = leaves (n1 = leaf 1, i.e. first leaf sampled on a specific plot)

x = number of sites sampled

y = number of plots sampled at each site

note: If only three leaves are sampled, then n4 and n5 are duplicate readings on n1 and n2 respectively conducted during cycle 4.

FIG. 2.6 Pre-dawn leaf water potential measuring sequence.

PLWP was a fairly good indicator of FMS in wheat, durum wheat, and maize. However, Boedt & Laker (1985) reported serious doubts regarding the validity of the leaf water potential as a parameter for FMS under extreme climatic conditions. It was therefore decided to check also for visual stress symptoms. These symptoms were described by Hensley & De Jager (1982) as follows: "It was found that when stressed the portions of a maize leaf on either side of the midrib tended to fold together. This caused the leaves to stiffen and to stand up at a relatively steep angle to the stem rather than droop in a gracious arc away from the plant. The stressed plants had a spiky appearance from a distance and leaves lost their luscious green colour and developed a greyish tinge with whitish stripes on the back of the leaves." Hensley & De Jager (1982) and Mallett & De Jager (1971) indicated that occurrence of these symptoms at 10h00 or 10h30 indicated soil induced water stress. Boedt & Laker (1985) found that plants showed these symptoms at 10h00 at Vaalharts in soils at all soil water levels, even at field capacity, due to the extreme climatic conditions. They then decided to use wilting at 9h00 as an indicator of FMS. Observations during this study at the Cradock Experimental Station confirmed the conclusions made by Boedt & Laker (1985). On days characterized by high evaporative demand, the maize plants, even in soils near or at field capacity level, showed these symptoms already at 10h00. At 9h00 these symptoms were only observed in plants in soils of which at least 80% of the PAWC was extracted.

2.4.5.3 Stem elongation measurements (wheat and durum wheat)

The effects of soil water stress on the growth of wheat and durum wheat was studied by monitoring the stem elongation of the plants. Ten plants per plot were chosen randomly very early in the season and their length was measured regularly until natural growth stopped. The term "natural" indicates that a stop in growth caused by soil water stress was not considered as the end of the growth of the plant because upon rewatering growth was normallly resumed. As the soil surface was constantly changed by irrigations and by walking through the plots, a reference height had to be defined. The two most important conditions were that the reference level had to be stable and easily retrievable. At first ropes were put across the plots in a level position close to the ground surface. This reference level was not very stable as the ropes stretched after some time. The level was also too high because the ropes had to be at a certain height above the soil surface in order not to be submerged when the plots were irrigated. It was then decided to put long steel nails in the soil as close as possible to the plant and to use their heads as a reference level which was about 15mm above the soil surface. The nails, labelled with numbers, could easily be found back and their position remained undisturbed after irrigation. This simple measuring method proved to be very successful and yielded some very interesting results as will be discussed later in Chapter 3.

2.4.5.4 Leaf expansion measurements (maize)

Leaf area expansion was selected as the parameter to study the effects of soil water stress on plant growth in maize. During the 1985-1986 season the growth of five randomly selected plants was monitored on each plot. Each plant was marked by putting a labelled nail next to it into the soil to make sure that the readings were always done on the same plant. A leaf area parameter was established using the length of a leaf and the width taken in the centre. The length (mm) was multiplied by the width (mm) and divided by a factor of 100. Summation of this product for all the leaves of one plant gave the leaf area parameter (LAP). A similar leaf area determination was used by Denmead & Shaw (1960).

The actual leaf area is smaller but can be calculated from these data. Judging by the shape of the leaf the actual area will more or less be equal to the leaf area parameter multiplied by a factor 0,75. This factor was also suggested by Stickler, Wearden & Pauli (1961) for sorghum leaves, which are similar to maize leaves in shape. Mallet (1972) used a factor of 0,78 for maize leaves. This results in the following equations:

L.A.P. = sum of [(L x B) / 100]

with L = length of the leaf (mm)
B = width of a leaf in the middle (mm), i.e. halfway between the base and tip

Actual leaf area = L.A.P. x 100 x 0,78 (sq.mm)

= L.A.P. x 78 (sq.mm)

During leaf expansion studies a certain relation was noticed between the length of a leaf and its width taken in the centre. This led to further research from which an equation expressing the relation between the total length of all the leaves and the leaf area parameter was derived. This made leaf expansion measurements less complicated as only the length had to be measured now and the leaf area parameter and the leaf area index could be calculated from these data. This saved a lot of time and more plants could be monitored. Statistical analysis of the data obtained during the 1985-1986 summer season at sites D6, D12 and D16 resulted in the following regression equations:

L.A.P. = (1,125 x L) - 1897
with L = total length of all the leaves (mm)

Actual leaf area = [(1,125 x L) - 1897] x 78
with L = total length of all the leaves (mm)

The leaf area index is per definition equal to the ratio of the total leaf area to the ground surface occupied by the plant. The area occupied by the plant for a planting density of 40000 plants per hectare is 0,25 square meter or 250000 square millimeter. This leads to the following equations:

Leaf area index = actual leaf area / 250000
= (78 x L.A.P.) / 250000
= L.A.P. x 0,000312
= [(1,125 x L) - 1897] x 0,000312
with L = total length of all the leaves (mm)

A complete statistical analysis can be found in Appendix 2.3.

2.4.5.5 Stem elongation measurements (maize)

Stem elongation of maize was intensively studied during the 1987-1988 summer experiments at site ISO-B. On each plot one plant was chosen in one of the central rows and a labelled nail was put next to it. Stem elongation measurements consisted of the measurement of the total length of the stem and of the distances between successive leaves. Total length was taken as the distance between ground level (zero reference point) and the point at which the youngest leaf was attached to the stem. The distance between two successive leaves was defined as the distance between the points at which the leaves were attached to the stem. The point at which the first leaf (lowest positioned leaf) was attached to the stem was per definition taken as the zero reference point.

2.4.6 Measuring techniques used during the detailed ecophysiological studies

2.4.6.1 Leaf water potential measurements

Diurnal leaf water potential measurements were done according to the same pressure chamber technique descibed for pre-dawn leaf water potential measurements in Section

2.4.5.2.

2.4.6.2 Net carbon-dioxide exchange rate (NCER)

NCER measurements were made during one of the three detailed studies (Ceulemans, Impens, Laker, Vanassche & Mottram, 1988). A portable, closed system including a small plexi clamp-on cuvette (inner area 3 square cm), an electronic timer differentiator and an infrared gas analyser (Leybold-Heraeus, type Binos 1, FRG) was used to measure NCER in the field as described earlier by Ceulemans, Kockelberg & Impens (1986). A small fan was also incorporated in the gas exchange system to thoroughly stir the air in the closed loop. Constant carbon-dioxide depletions of 5-10 cubic cm per cubic meter in the system were always maintained.

To reduce interplant variability, NCER measurements were made on the last (youngest) fully expanded sunlit leaves, which have the highest NCER values (Baldy, 1986; Dwyer & Stewart, 1986). Leaves were held horizontally during the measurements so that azimuthal influences were eliminated. Ten different standard leaves were sampled each time and measurements were carried out on average 11 times a day. Measuring periods were taken consecutively on stressed and unstressed plots and each period lasted for about 10 minutes.

2.4.6.3 Stomatal conductance

Stomatal diffusion conductance to water vapour was measured during two of the three detailed studies (Ceulemans, Laker & Vanassche, 1988; Laker, Ceulemans & Vanassche - Appendix 3.4). It was measured with an automatic, ventilated diffusion porometer. The original instrument (Cayuga Development, USA), described by Carbonneau (1983), has been automated, improved and modified considerably by F. Kockelbergh in the Department of Biology, University of Antwerp. A Vaisala Humicamp (Finland) humidity sensor with a complete electronic display and cycling circuit has been incorporated in the system, while the chamber volume has been reduced considerably. The inner area of the cuvette was 1 square cm and the constant sampled humidity range was as narrow as 3%. This improved version of the porometer had been tested under a wide range of humidity and temperature conditions, but was used for the first time in a research experiment in the present study.

Porometer cuvette temperature was measured by an inner copper-constantan (Omega Inc., USA) thermocouple.

Diurnal measurements of stomatal conductance were made at two-hour intervals from sunrise to sunset on the lower surface of maize leaves during the one study (Ceulemans et al., 1988b) and during early morning (about 08h00), midday (about 13h00) and afternoon (about 16h00) in the other study (Laker et al., Appendix 3.4). Mature, fully expanded leaves of five or six different plants were sampled for replicate determinations at any time and gs readings were always taken in the middle of the leaf beside the midvein. Sets of replicates were sampled from different experimental plots with different soil water deficits.

The equation for converting stomatal resistance, measured with the porometer, to conductance is given by Ceulemans et al. (1988b).

Immediately after each stomatal conductance measurement, measurements were also made of leaf water potential, vapour saturation deficit, leaf temperature, air temperature and photosynthetically active radiation.

2.4.6.4 Photosynthetically active radiation (PAR)

Incoming PAR or photosynthetic photon flux density (PPFD) was measured with a Lambda quantum sensor (type Li-190 SB, LiCor, USA) connected to a multichannel Deltalogger.

2.4.6.5 Leaf temperature

Leaf temperatures were measured with small, thin copper-constantan thermocouples connected via a special thermocouple connector to a standard reference junction incorporated in a digital millivolt read-out unit. The physical and electrical equivalent of an ice bath reference thermocouple at 0°C was provided by a reference junction which was built into a portable, battery-operated read-out unit developed and constructed by F. Kockelbergh in the Department of Biology, University of Antwerp. Hence, temperatures could directly be read out in the field on the digital display unit. Furthermore, PAR could be displayed on the same unit.

Leaf thermocouples were sealed in an aluminium hair clip and could easily be attached to or detached from leaves without any damage. Four thermocouple clips were attached to different leaves each time. The digital hand-held read-out unit was protected by adhesive aluminium foil to give a high degree of insulation so that no direct temperature effects on the electronic compensation units were noticed.

The thermocouples were clamped to the lower surfaces of 10 randomly selected upper canopy leaves. Leaf temperature readings of the 10 replicates were averaged each time. Care was taken to ensure that the thermocouples were not exposed to direct sunlight during readings.

2.4.6.6 Vapour saturation deficit (VSD) and air temperature

Atmospheric humidity and air temperature were measured next to the experimental plots with a forced ventilation Assman-type psychrometer.

CHAPTER 3

PAWC VALUES OF WHEAT, DURUM WHEAT AND MAIZE AT DIFFERENT GROWTH STAGES AND THE EFFECTS OF SOIL WATER STRESS AT DIFFERENT GROWTH STAGES ON VEGETATIVE GROWTH AND GRAIN YIELD

3.1 INTRODUCTION

During the 1985 winter season PAWC determinations at different growth stages were done with wheat at sites D6 and D12. At each site five plots (5m by 5m) were planted. These were stressed at different stages. Due to managerial problems at the beginning of the experiments (before the researcher arrived) and unfavourable weather conditions towards the end of the season there were some doubts regarding the validity of the data collected during this season. The experiments were, therefore, repeated at sites D6, D12 and D16 during the 1986 winter season, using five plots of 5m by 5m per site. One of the five plots was retained as a well-watered control throughout the whole season, receiving water as soon as

50% of PAWC was extracted. Site D16 was included from this season onwards in order to obtain results for more varied soils.

PAWC determinations with durum wheat at different growth stages were conducted during the 1987 winter season at sites D6, D12 and D16. Five plots (5m by 5m), one of which was used as a well-watered control, were planted at each site.

During the 1985-86 summer season PAWC determinations at different growth stages with maize were done at sites D6, D12 and D16. Five plots (5m by 5m), of which one was used as a well-watered control, were planted at each site. Due to severe hail damage leaf expansion studies could not be completed successfully during this season. These experiments were, therefore, repeated at sites D6 and D12 during the 1986-87 summer season. An extensive irrigation scheduling experiment with maize was conducted at site ISO-B during the 1987-88 season to determine the effects of water stress at different growth stages on leaf expansion, stem elongation and yield.

During the 1985-86 summer season two short-term detailed eco-physiological studies were conducted at different plots of the irrigation scheduling experiment with maize (reported in Chapter 4). By measuring NCER or stomatal conductance in plants on plots at different degrees of water stress simultaneously an indication of the effects of water stress on these parameters could be obtained over a short period of time. These parameters were used to verify the validity of the lower limit of PAWC (i.e. FMS) as determined by means of pre-dawn leaf water potentials (PLWP) and visual symptoms. During the 1986-87 summer season stomatal conductance studies with maize were conducted at site D16 on plots on plots at different degrees of water stress. Again this was a detailed short-term experiment with different degrees of water stress being induced simultaneously.

Mature stage PAWC determinations with wheat, durum wheat and maize were also made at site ISO.

A list of cultivars and planting, emergence and flowering dates is given in Table 3.1.

TABLE 3.1 - Cultivars and dates of planting, emergence and flowering of wheat, maize and durum wheat at sites D6, D12 and D16

Wheat	Cultivar	Planting	Emergence	Flowering
1985				
D6	Zaragossa	8/07/1985	20/07/1985	21/10/1985
D12	Zaragossa	9/07/1985	20/07/1985	21/10/1985
1986				
D6	Gamtoos	16/06/1986	29/06/1986	3/10/1986
D12	Gamtoos	18/06/1986	29/06/1986	3/10/1986
D16	Gamtoos	18/06/1986	29/06/1986	3/10/1986
Durum wheat				
1987				
D6	Moni	22/06/1987	6/07/1987	16/10/1987
D12	Moni	22/06/1987	6/07/1987	16/10/1987
D16	Moni	22/06/1987	6/07/1987	16/10/1987
Maize				
1985-86				
D6	Pioneer PNR 542	6/11/1985	13/11/1985	24/01/1986
D12	Pioneer PNR 542	6/11/1985	13/11/1985	24/01/1986
D16	Pioneer PNR 542	6/11/1985	13/11/1985	24/01/1986
1986-87				
D6	Pioneer PNR 542	20/10/1986	27/10/1986	13/01/1987
D12	Pioneer PNR 542	20/10/1986	27/10/1986	13/01/1987
1987-88				
ISO	Pioneer PNR 6528	20/10/1987	27/10/1987	10/01/1988
Eco-physiological studies				
Maize				
1985-86				
ISO	Pioneer PNR 542	29/10/1985	8/11/1985	17/01/1986
1986-87				
D16	SNK 2244	1/10/1986	10/10/1986	22/12/1986

3.2 RESULTS

3.2.1 Wheat

The different growth stages of wheat at which the different drying cycles were started during the 1985 and 1986 seasons are listed in Table 3.2. It should be kept in mind that during 1985 the studies were conducted only at sites D6 and D12, whereas sites D6, D12 and D16 were all included during 1986.

TABLE 3.2 - Growth stages at which drying cycles for wheat were started during the 1985 and 1986 winter seasons

Plot no.	Growth stage at start of drying cycle		
	Phenological stage *	Days after planting 1985	1986
a	3	35	42
b	5	55	52
c	7	68	62
d	8	75	72
f	flowering	100	n.a.

* Phenological stages according to Large (1954):
Stage 3: Tillering.
Stage 5: Leaf sheaths strongly erected.
Stage 7: First node of stem visible.
Stage 8: Flag leaf just visible.

3.2.1.1 Winter 1985

3.2.1.1.1 Stem elongation and leaf water potential

On plot D6a the stem elongation dropped sharply to below that of the other plots on day 13 of the drying cycle. It remained fairly constant for another five days, before it started decreasing further to reach zero on day 23 of the drying cycle, i.e. day 58 after planting (Figures 3.1 and 3.2). PLWP remained constant at -150kPa for 12 days after the start of the drying cycle. On day 13 it dropped to -600kPa, where it remained until day 23. On day 24, the day after growth stopped, it dropped sharply to -1500kPa (Figure 3.3).

The stem elongation pattern found on plot D12a was similar to that on D6a (Appendices 3.1.1 and 3.1.2). As on plot D6a PLWP dropped sharply after day 12, but in this case to a much lower value (about -1000kPa) than on plot D6a (about -600kPa). Compare Figure 3.3 and Appendix 3.2.1. This difference was possibly due to the restricting layer in plot D6a, which created a better water supply to the top part of the root system during the latter part of the drying cycle. Similar conclusions were drawn according to the results of other studies on this soil, which are reported later in this chapter. It

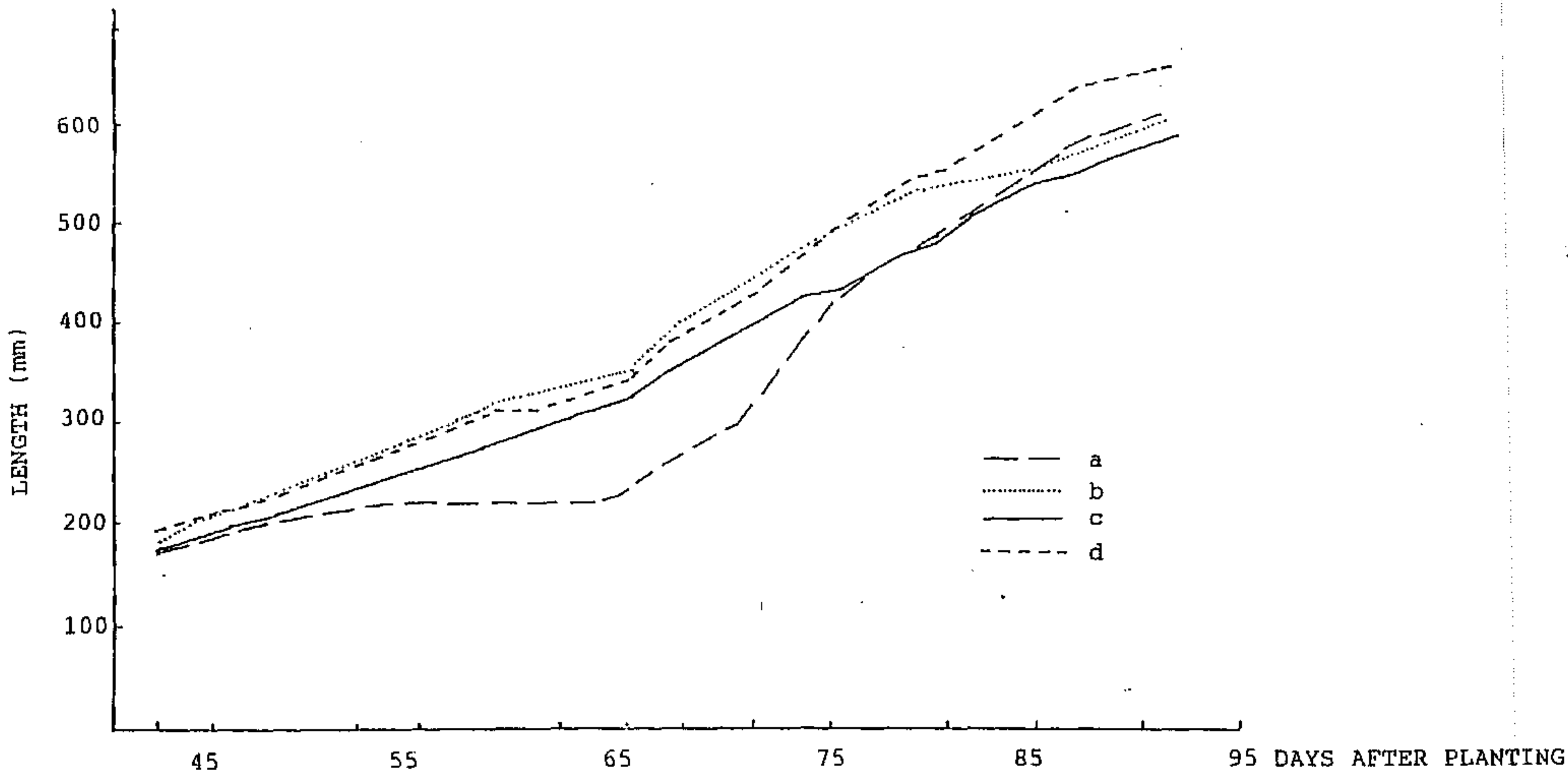


FIG.3.1 CUMULATIVE STEM ELONGATION OF WHEAT AT SITE D6 (1985 SEASON)

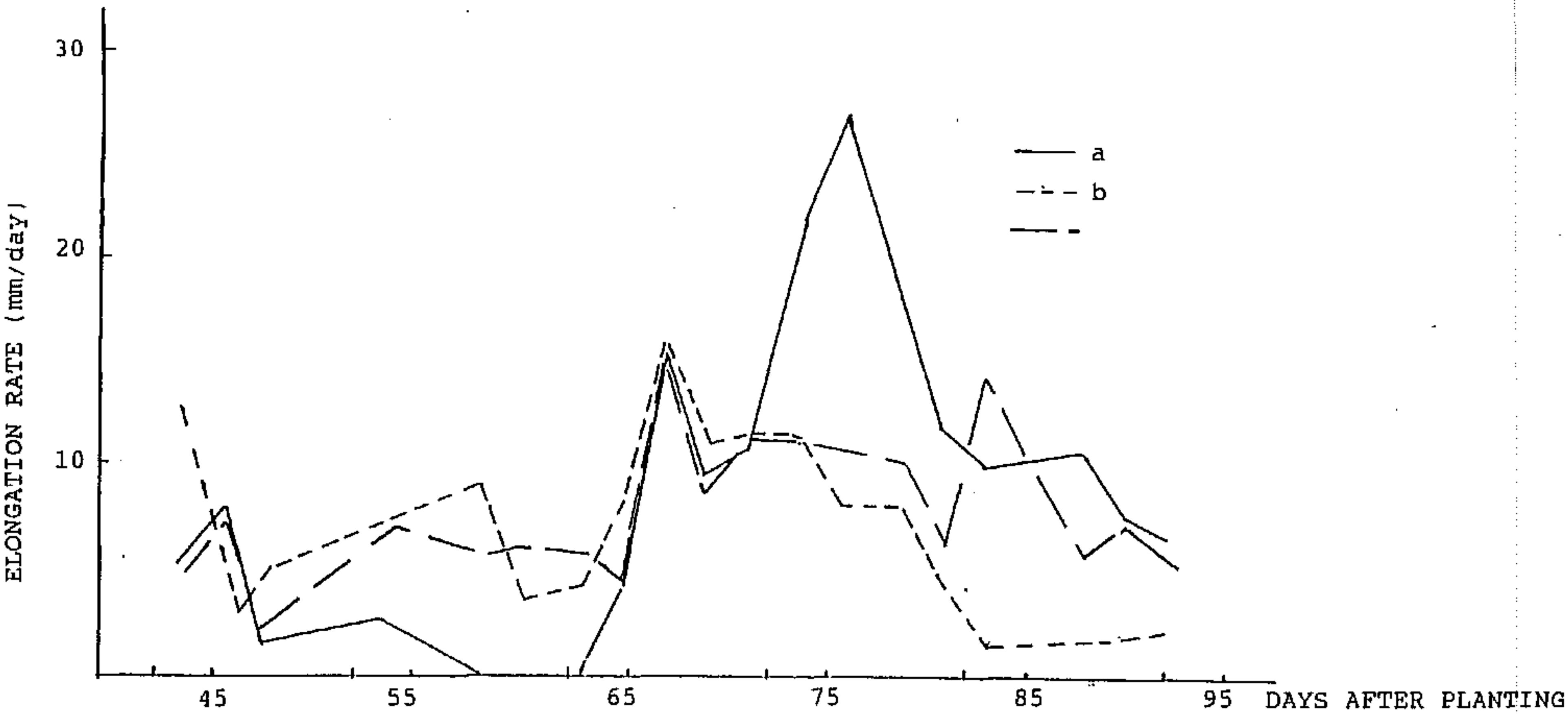


FIG.3.2 STEM ELONGATION RATE OF WHEAT ON PLOTS D6a AND D6b (1985 SEASON)

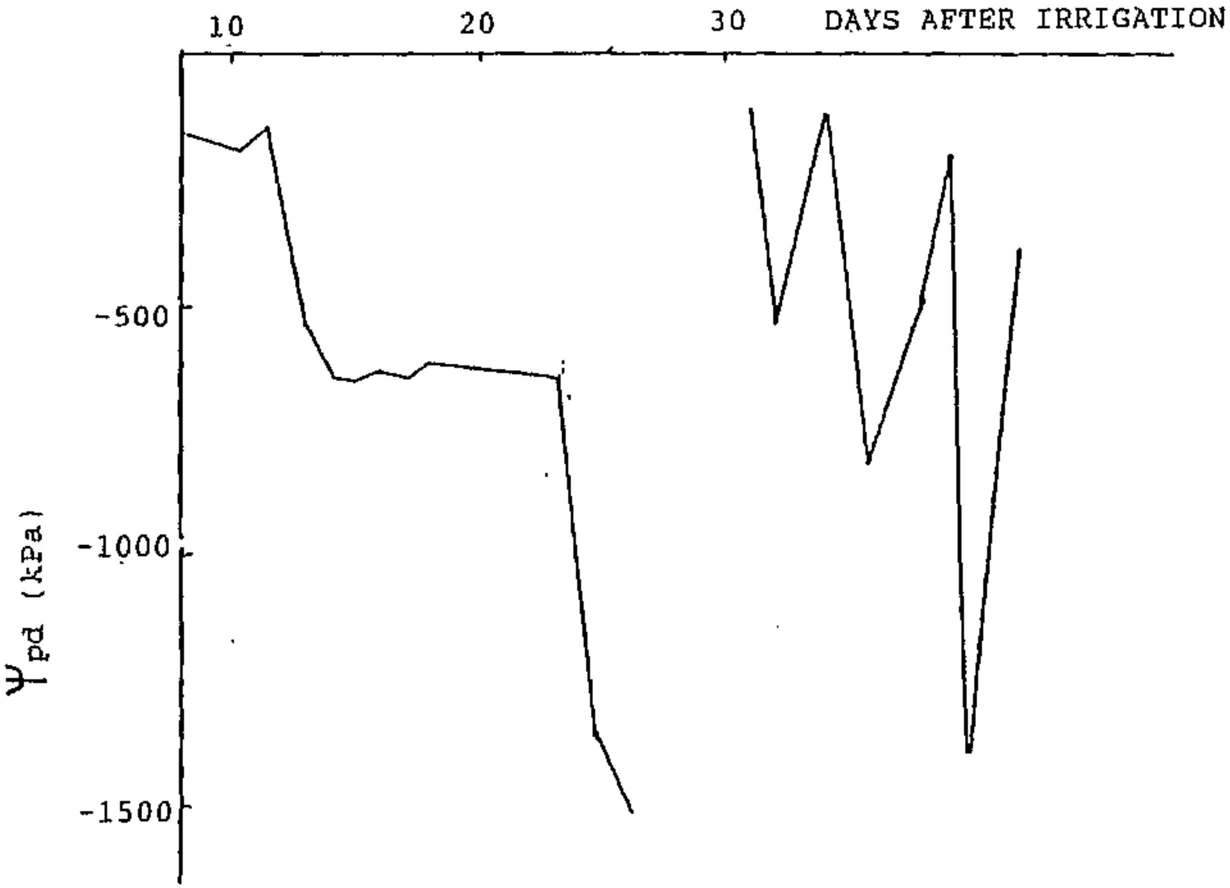


FIG.3.3 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D6a. (1985 SEASON)

is noticable that PLWP on D12a was also during the first 12 days of the drying cycle lower than on D6a.

It can be concluded that on both plots D6a and D12a an initial stress, which can be equated with FMS, clearly set in on day 13 of the drying cycle. By day 23 severe stress, which agrees with the in situ measured lower limit (LOL) of the PLEXW concept of Ratliff et al. (1983), i.e. when plants become dormant due to water stress, occurred.

The drying cycle was continued for another five days, inducing severe stress conditions. When irrigated (on day 29), the plants responded immediately: PLWP increased overnight to values of -150kPa and the stem elongation rate rose very sharply and after some days became even higher than on the other three plots. The plants ended up comparable in size to the plants on the other plots.

Stem elongation rates on D12a were higher than on D6a after the first irrigation after the stress period but lower after the second one. This resulted in the same height of the plants as on D6a at the end of the growing season. The higher elongation rates on plot D12a after the first irrigation were probably the result of the better drainage characteristics of this soil. The water reached the deeper root zone much quicker on plot D12a while on plot D6a the water front moved much slower, causing temporary waterlogged conditions as the macro pores were filled with water for a longer period.

On plot D6b, where the drying cycle was started 55 days after planting, the cumulative stem elongation was equal to that of the plants on plots D6c and D6d, which were unstressed, during the first nineteen days of the drying cycle (Figure 3.1). Their stem elongation rate patterns were also identical (Figures 3.2 and 3.5). Then the stem elongation rate of D6b started decreasing relative to those on D6c and D6d. It again initially dropped to a plateau, after which it dropped to a very low value nine days later (Figure 3.2). The plants did not become dormant, however, as in the case of the a plots. A first definite drop in PLWP (to -1150kPa) occurred nineteen days after the start of the drying cycle, i.e. on the day on which the stem elongation rate started decreasing relative to D6c and D6d (appearance of flag leaf, stage 8 according to Large, 1954). For most of the preceding period PLWP fluctuated around -500kPa. This first drop in PLWP did not clearly indicate FMS as much higher values were measured again afterwards (Figure 3.4). From this time on PLWP fluctuated very sharply, with decreasing minima to the oscillations (Figure 3.4). This type of

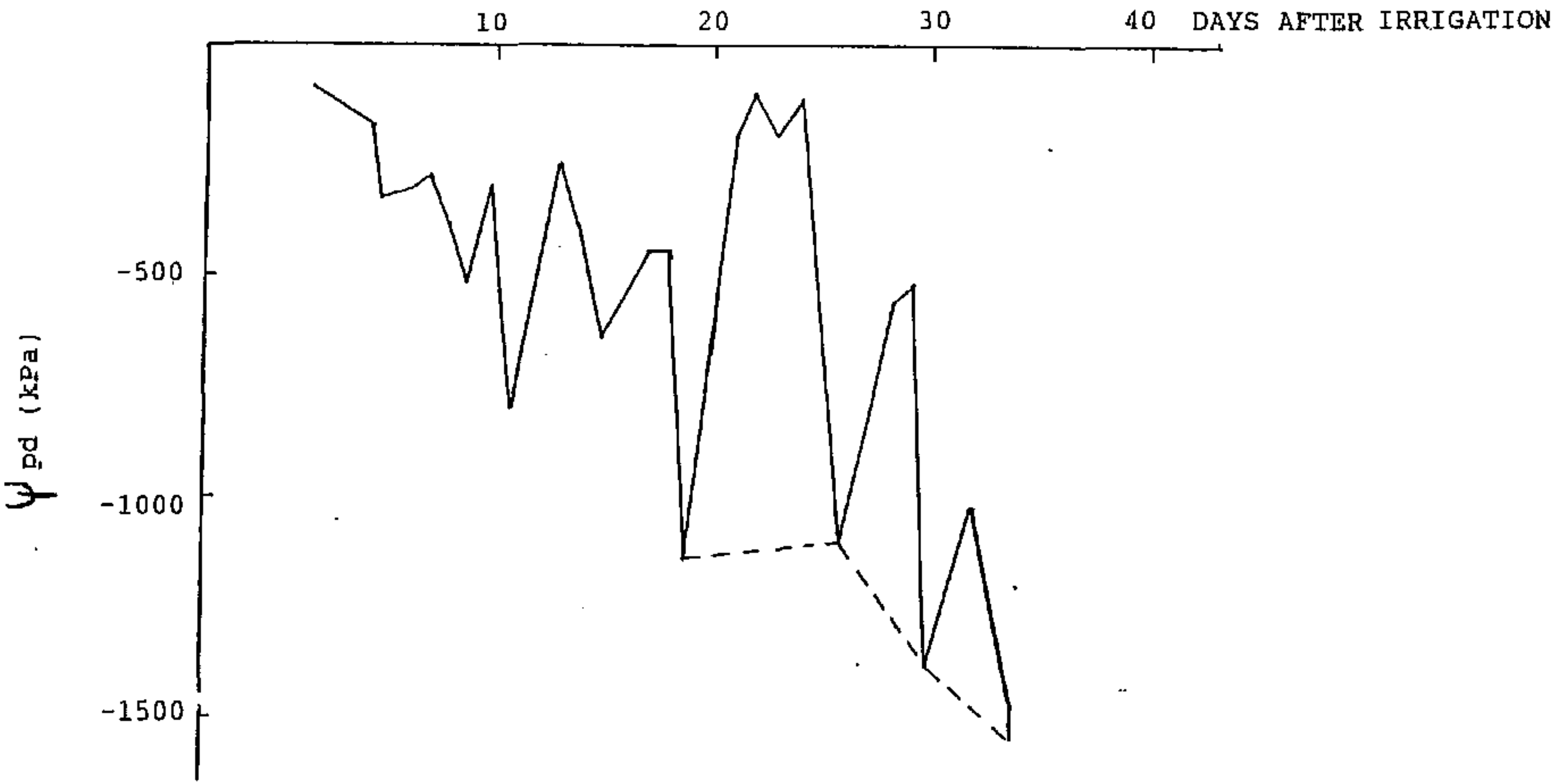


FIG.3.4 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D6b (1985 SEASON)

pattern was also identified by Boedt & Laker (1985). On day 30 of the drying cycle a PLWP value of -1500kPa was reached, coinciding with the onset of a period of very slow growth due to water stress.

The results from plot D12b, presented in Appendices 3.1.1, 3.1.2 and 3.2.2, again, as in the case of the a plots, showed certain similarities and certain important differences compared with D6b. Similarities include PLWP fluctuating around -500kPa for most of the first 19 days, the sharp drop on day 19 (in the case of D12b even lower than on D6b) and the strong fluctuations thereafter to reach less than -1500kPa on day 30. The major difference is that stem elongation rate for D12b linearly dropped to a low value after day 19 of the drying cycle and not to an initial plateau as for D6b. This is possibly again linked to the sustained water supply to the upper part of the root zone on D6 due to the restricting layer at 700mm. Both plots D6b and D12b were irrigated again on day 31 of the drying cycle.

The stem elongation rate of the plants on plot D6c was similar to the rate found on plot D6d for the first six days of the drying cycle (Figure 3.5), giving parallel running cumulative stem elongation lines (Figure 3.1). For the next few days the stem elongation rate on D6c

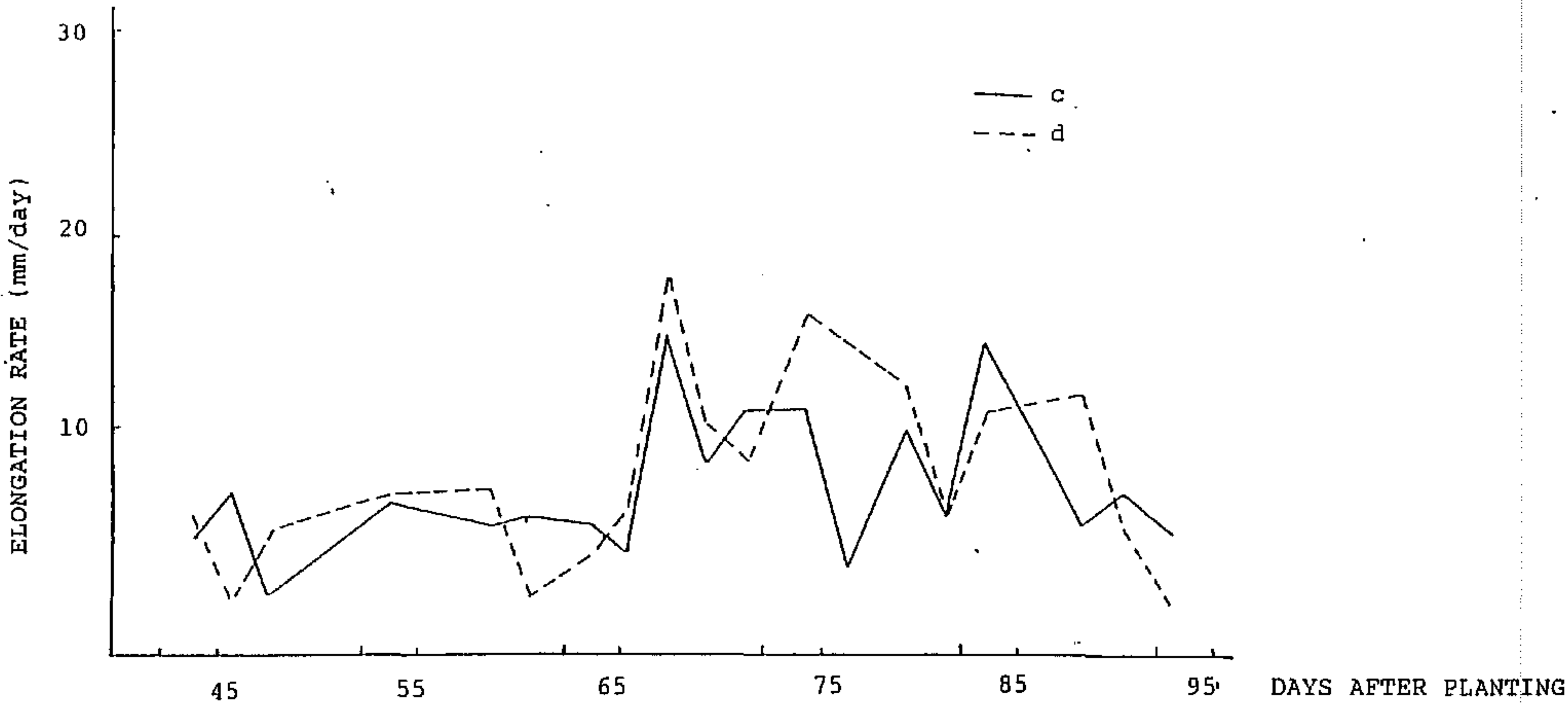


FIG.3.5 STEM ELONGATION RATE OF WHEAT ON PLOTS D6c AND D6d (1985 SEASON)

dropped far below that for the well-watered D6d, after which the values for the two plots became similar again. This initial drop in elongation rate was not due to soil-induced water stress but extreme temperatures developing under the plastic covers on D6c on a few very hot days (D6d was not covered during this period). After day 16 of the drying cycle the elongation rate on D6c dropped sharply to reach a low value on day 20, indicating FMS. The PLWP pattern of plot D6c seems very irregular because of the sharp fluctuations at the beginning of the drying cycle (Figure 3.6). Of particular importance is the sharp drop on day 6, the day on which stem elongation decreased sharply. These drops were caused by the "greenhouse" effect, induced by the plastic covers for protection against rain. Very high temperatures (above 30 C) during this period caused even higher temperatures under the plastic covers as the heat could not escape. The plastic covers could not be removed during this period because of the high possibility of thunderstorms in the afternoons. The fact that the drops in PLWP on plot D12c occurred on the same dates supports this theory (Appendix 3.2.3). FMS, as indicated by the drop in stem elongation on day 20, was confirmed by the drop in PLWP to nearly -1500kPa 23 days after the final irrigation.

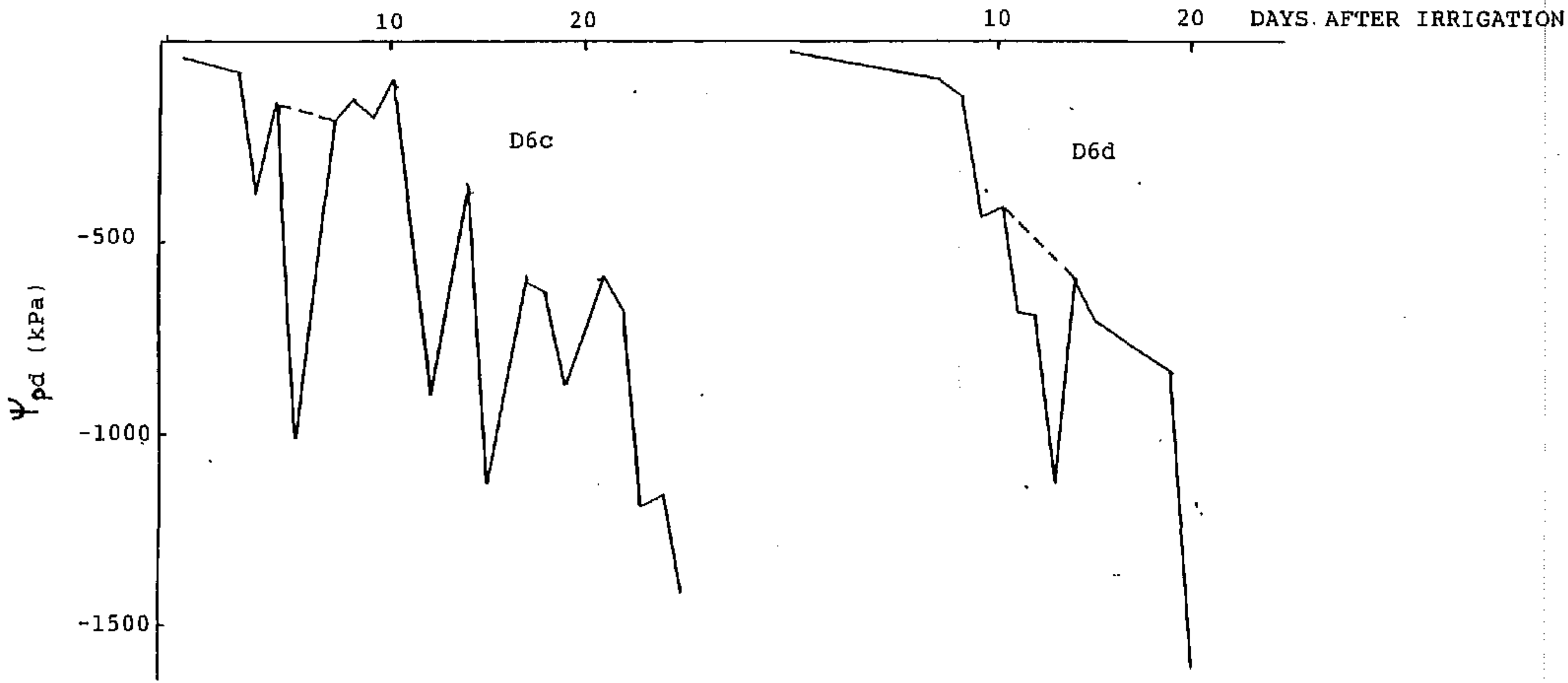


FIG.3.6 PRE-DAWN LEAF WATER POTENTIAL PATTERNS OF WHEAT ON PLOTS D6c AND D6d (1985 SEASON)

The leaf elongation patterns of plot D12c are similar to those of D6c (Appendices 3.1.1 and 3.1.3). The stem elongation rate again dropped relative to D12d early during the cycle when the extreme temperature conditions prevailed. It also recovered briefly before dropping sharply after day 16 to reach a low value on day 18 of the drying cycle, indicating FMS. The drop in PLWP to -1500kPa on day 19 of the drying cycle confirmed the onset of FMS (Appendix 3.2.3). The stress treatment was continued for seven days after the onset of FMS on both plots D6c and D12c.

The drying cycle on plot D6d as well as on plot D12d did not have any effect on the stem elongation and in both cases the plants were taller than the plants on the other plots (Figure 3.1 and Appendix 3.1.1). The drop of the stem elongation rate, 17 days after the final irrigation, was a result of the termination of the vegetative growth stage and was not induced by stress conditions. This is supported by the drop of the rate on all plots (Figure 3.5 and Appendices 3.1.2 and 3.1.3). FMS was identified on both plots by the drop in PLWP. The drops were observed on plots D6d and D12d respectively 19 and 17 days after the start of the drying cycle (Figure 3.6 and Appendix 3.2.3). The drying cycles were continued for seven days after the onset of FMS on both plots D6d and

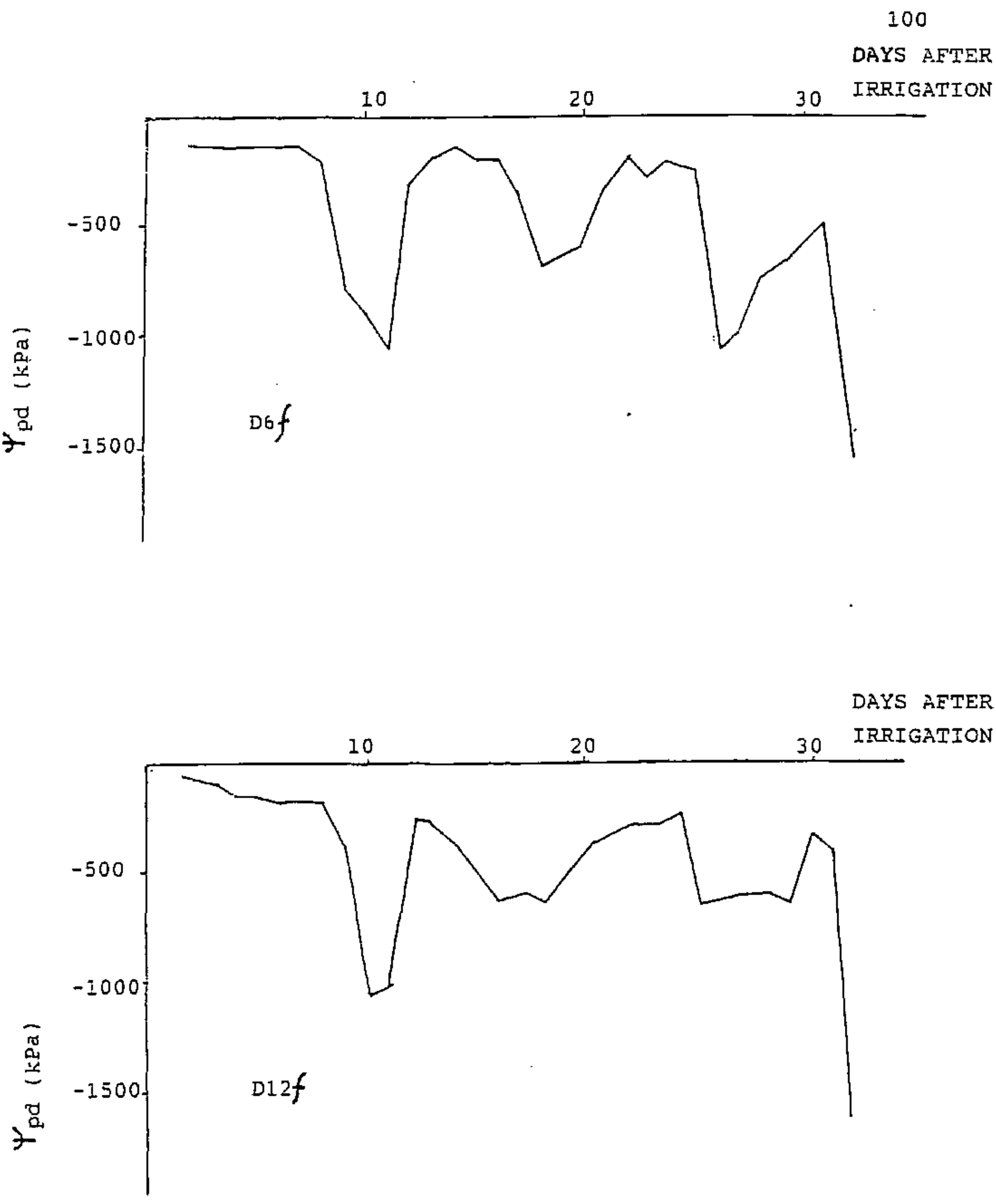


FIG.3.7 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOTS D6f AND D12f (1985 SEASON)

D12d.

The drying cycles on plots D6f and D12f were started at flowering stage in order to determine the maximum PAWC. The drop in PLWP occurred 31 days after the start of the drying cycles on both plots, indicating FMS (Figure 3.7). At the start of the drying cycle water demands were at peak level and started decreasing from that time onwards (see also Boedt & Laker, 1985). This explains the longer period to reach FMS.

The number of days to reach FMS, the phenological growth stage at which FMS was reached and the parameters which identified FMS are summarized in Table 3.3.

3.2.1.1.2 PAWC values and soil water extraction patterns

The soil water extraction patterns found at site D6 are shown in Figures 3.8 (a, b, c and d plots) and 3.9 (at flowering stage). All patterns show the same basic fan shape with time. The evolution of the patterns as the plants developed consisted mainly in the downward movement of the convergence point from a depth of 700mm on plot D6a to a depth of 1200mm on plot D6d.

TABLE 3.3 - Phenological stages at the start and end of the drying cycles, number of days to reach FMS and parameters used to identify FMS of wheat at different growth stages at sites D6 and D12 (1985 winter season)

Plot no.	Phenological stage * start	end	Days to FMS	Parameter **
D6a	3	5	13	PLWP* and SER
D6b	5	8	19	PLWP and SER
D6c	7	10	20	PLWP and SER
D6d	8	10.1	19	PLWP
D6f	flowering	grain filling	31	PLWP
D12a	3	5	13	PLWP* and SER
D12b	5	8	19	PLWP and SER
D12c	7	10	18	PLWP and SER
D12d	8	10.1	17	PLWP
D12f	flowering	grain filling	31	PLWP

* Phenological stages according to Large (1954).
Stage 3: Tillering.
Stage 5: Leaf sheaths strongly erected.
Stage 7: First node of stem visible.
Stage 8: Flag leaf just visible.
Stage 10: Ears in boot.
Stage 10.1: Appearance of the ears.

** Parameters.
PLWP : Pre-dawn leaf water potential.
PLWP*: At values higher than -1000kPa.
SER : Stem elongation rate.

Although the soil profile was not fully filled to field capacity before the start of the young growth stage experiments, soil water extraction from soil layers below 700mm at these stages was not markedly different from that at growth stage f (soil profile at field capacity at start of drying cycle). The low soil water extraction from layers below 700mm is explained by the presence of a

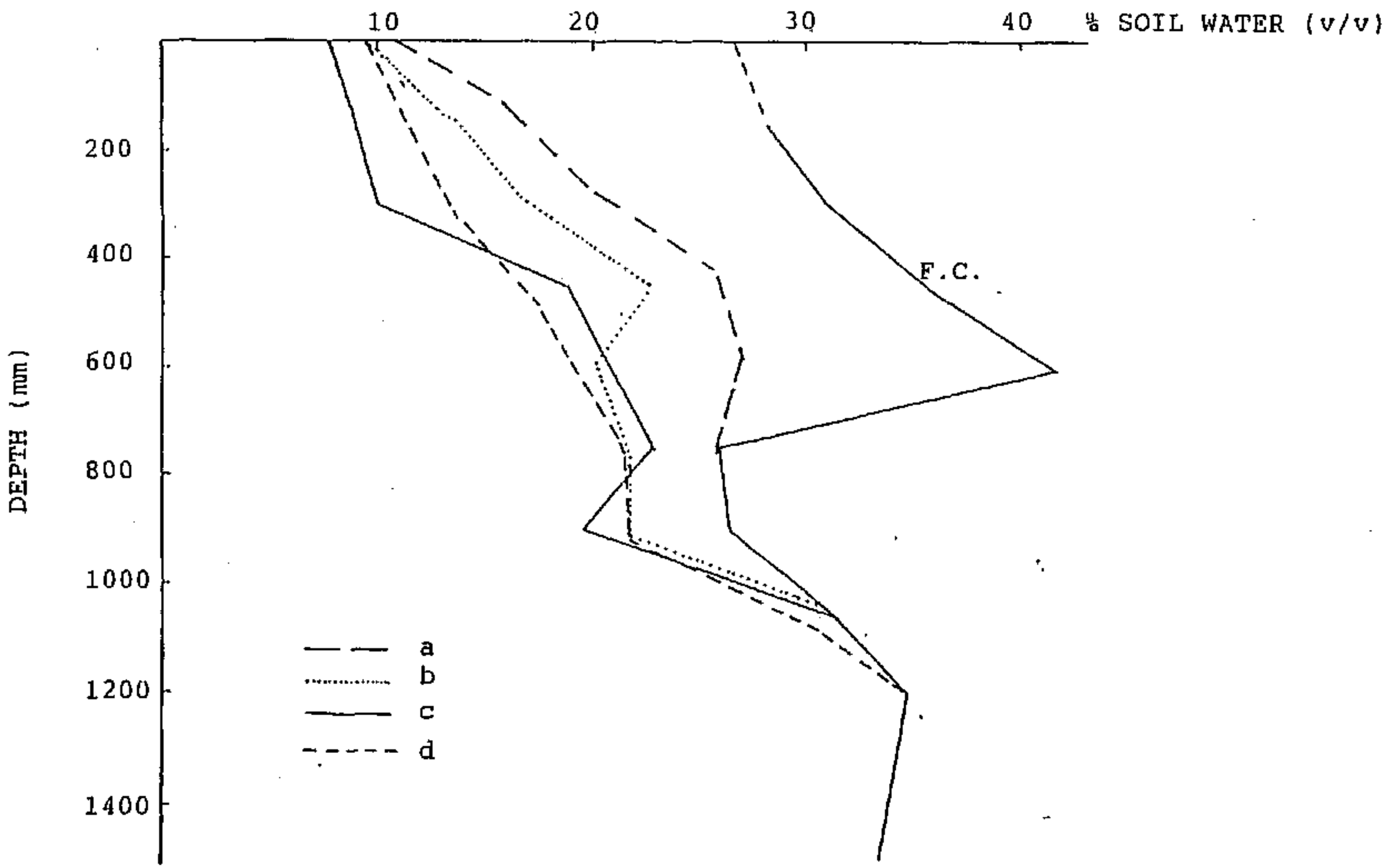
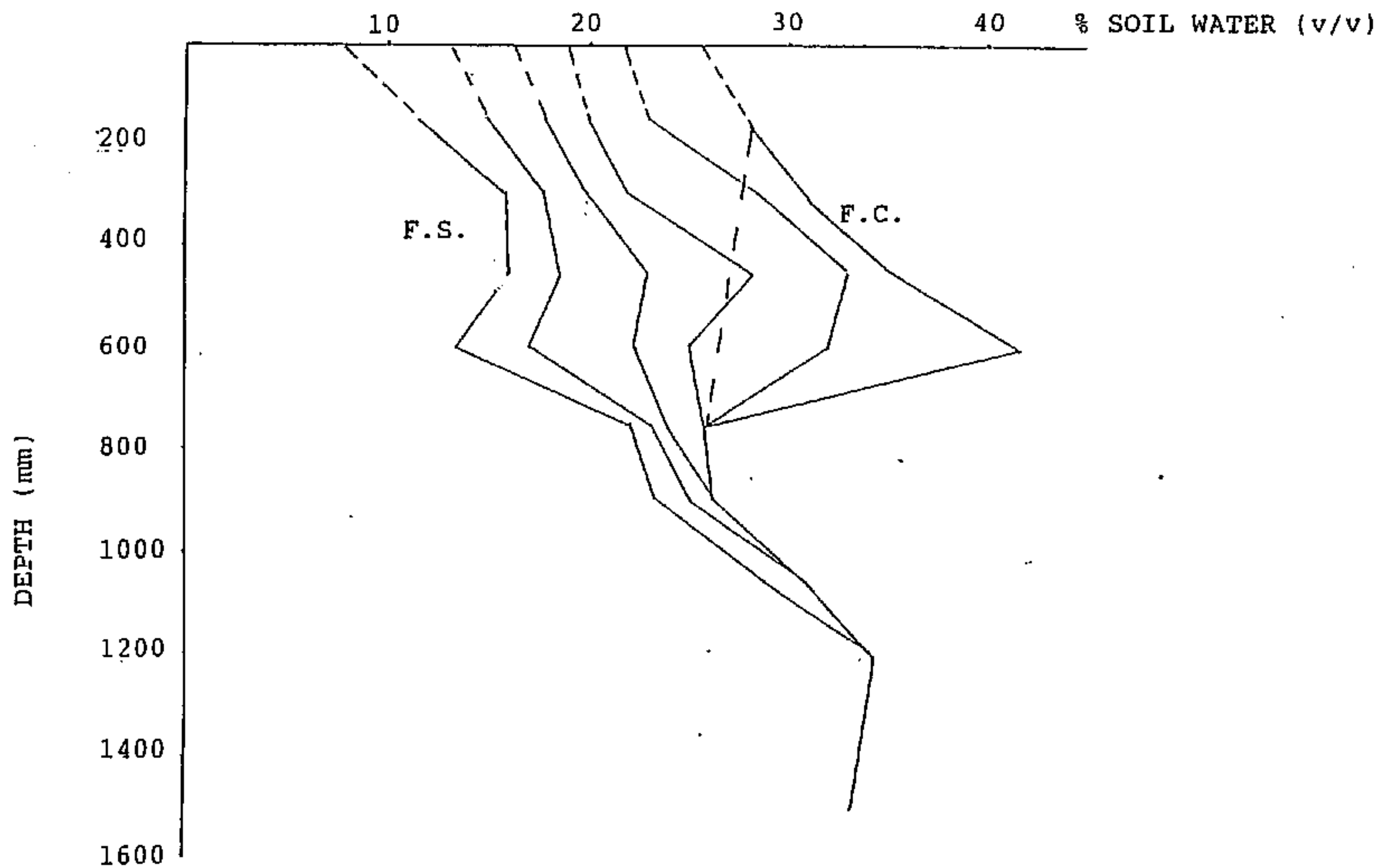


FIG.3.8 SOIL WATER EXTRACTION PATTERNS OF WHEAT AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D6 (1985 SEASON)

FIG.3.9 SOIL WATER EXTRACTION PATTERN OF WHEAT AT FLOWERING STAGE AT SITE D6. (1985 SEASON)



restricting layer with upper boundary at a depth of 600mm to 700mm, resulting in a very poor root development below this depth.

The presence of this restricting layer is clearly illustrated in the soil water extraction patterns (Figure 3.8). A first indication is the high apparent field capacity value above the resticting layer. The actual field capacity for this part of the profile is much lower. The higher value is a result of partial waterlogging. However, this water was also available to the plants and must be taken into account when calculating PAWC. A second characteristic is the high quantity of roots above this layer, illustrated by the high soil water extraction (first stress lines bulge to the left).

The quantities of soil water extracted at different depths and the PAWC values at each growth stage for site D6 are listed in Table 3.4. It is clear that the extraction below a depth of 700mm did not increase much as the plants grew older. The difference in soil water extraction from layers deeper than 700mm between growth stage a and growth stage d was about 11mm which was less than 10% of the final PAWC. The PAWC value found at flowering stage (140,2mm) was already reached at growth stage c (138,0mm). Figure 3.10 illustrates the evolution of the PAWC as the plants developed. The graph shows very clearly that the PAWC increased sharply during the early stages of the growing season and reached a maximum long before flowering stage. Superimposition of relative top growth and relative PAWC in Figure 3.10 shows that PAWC reaches its maximum earlier than top growth and that PAWC during young growth stages is relatively much higher than would be expected. The dotted line in Figure 3.10 illustrates the evolution of PAWC against the time it was determined, while the full line gives the relative PAWC against the time it can be applied in irrigation scheduling (i.e. when drying cycles can be started using the specific PAWC values).

TABLE 3.4 - Quantities of soil water extracted by wheat at different soil depths and PAWC values for each growth stage at site D6 (1985 season)

	water extracted (mm).				
depth (mm)	a	b	c	d	flowering
0- 100	13,3	15,5	18,7	16,5	17,0
100- 200	10,6	14,5	19,8	16,8	15,8
200- 300	10,3	14,3	20,7	17,5	15,0
300- 400	9,1	13,7	18,3	18,3	17,8
400- 500	10,6	16,2	18,0	19,5	22,3
500- 600	12,7	22,0	20,8	22,0	28,3
600- 700	6,1	10,0	8,3	10,0	12,5
700- 800		4,5	4,2	4,3	4,5
800- 900		4,8	6,7	4,5	3,0
900-1000		2,0	2,5	2,3	2,5
1000-1100					1,5
1100-1200					
PAWC	72,7	117,5	138,0	131,7	140,2

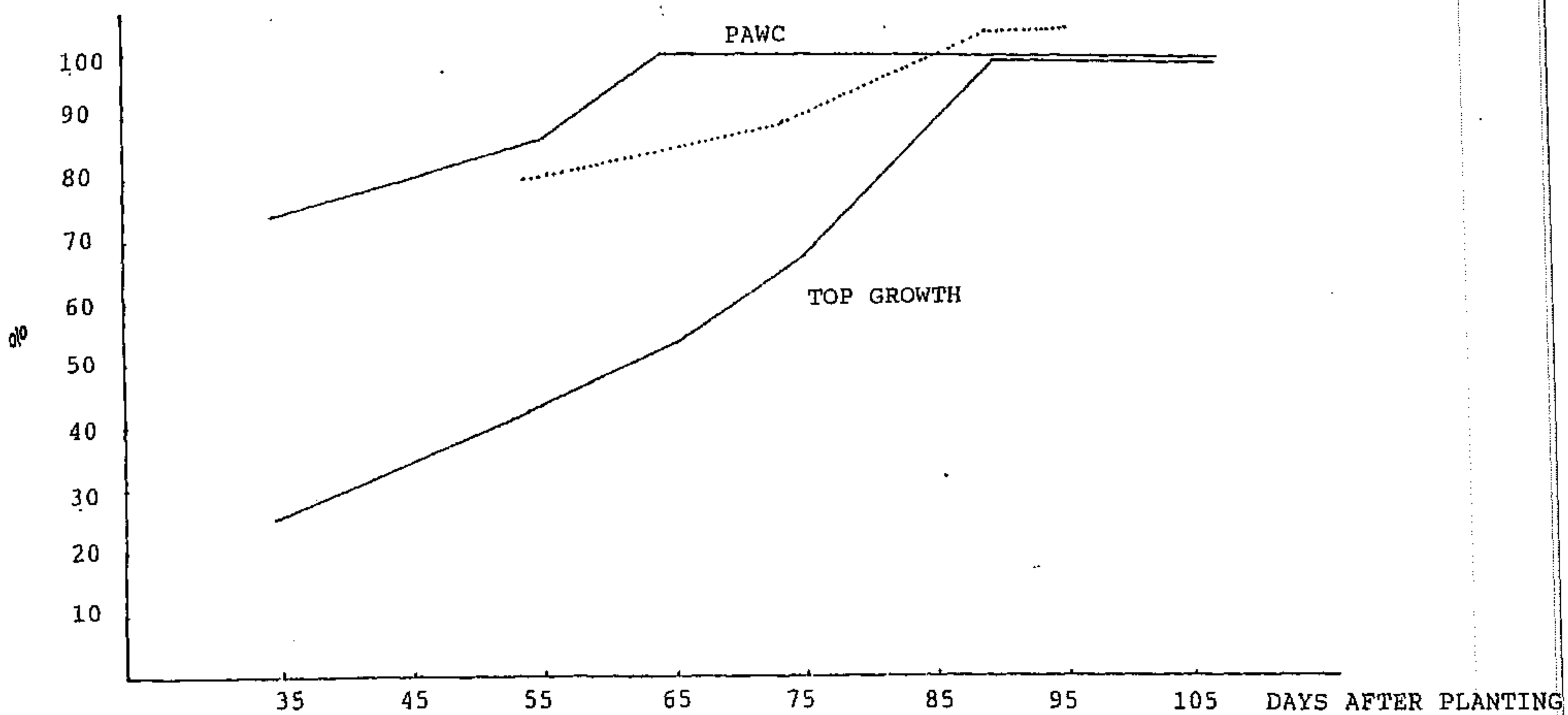


FIG.3.10 RELATIVE PAWC AND RELATIVE TOP GROWTH OF WHEAT AT SITE D6 (1985 SEASON)

The extraction patterns found at site D12 are given in Appendices 3.3.1 and 3.3.2. The patterns all have a fan shape. Their evolution consisted firstly in a downward movement of the convergence point from a depth of 900mm at growth stage a to a maximum depth of 1200mm at growth stage b and secondly in the opening of the fan (stage b to stage c). The extraction pattern at growth stage d is virtually the same as at growth stage c. Compared to the patterns found at site D6, more water was extracted from soil layers deeper in the profile. This confirms that the compacted soil layer at site D6 was the main reason for the poor root development in the deeper soil layers. The quantities of soil water extracted at different depths at different growth stages at site D12 and the PAWC values at each growth stage are listed in Table 3.5. As the evolution of the extraction patterns suggested, the maximum PAWC value was already reached at stage c, quite some time before flowering stage. As the plants developed, more water was extracted from soil layers deeper in the profile. An increase of more than 20% was found below a depth of 800mm between stage a and stage c. Figure 3.11 shows that the PAWC increased very sharply during the early vegetative growth stages to reach a maximum value quite some time before flowering stage. The meaning of the full and dotted PAWC lines is the same as for site D6 (Figure 3.10).

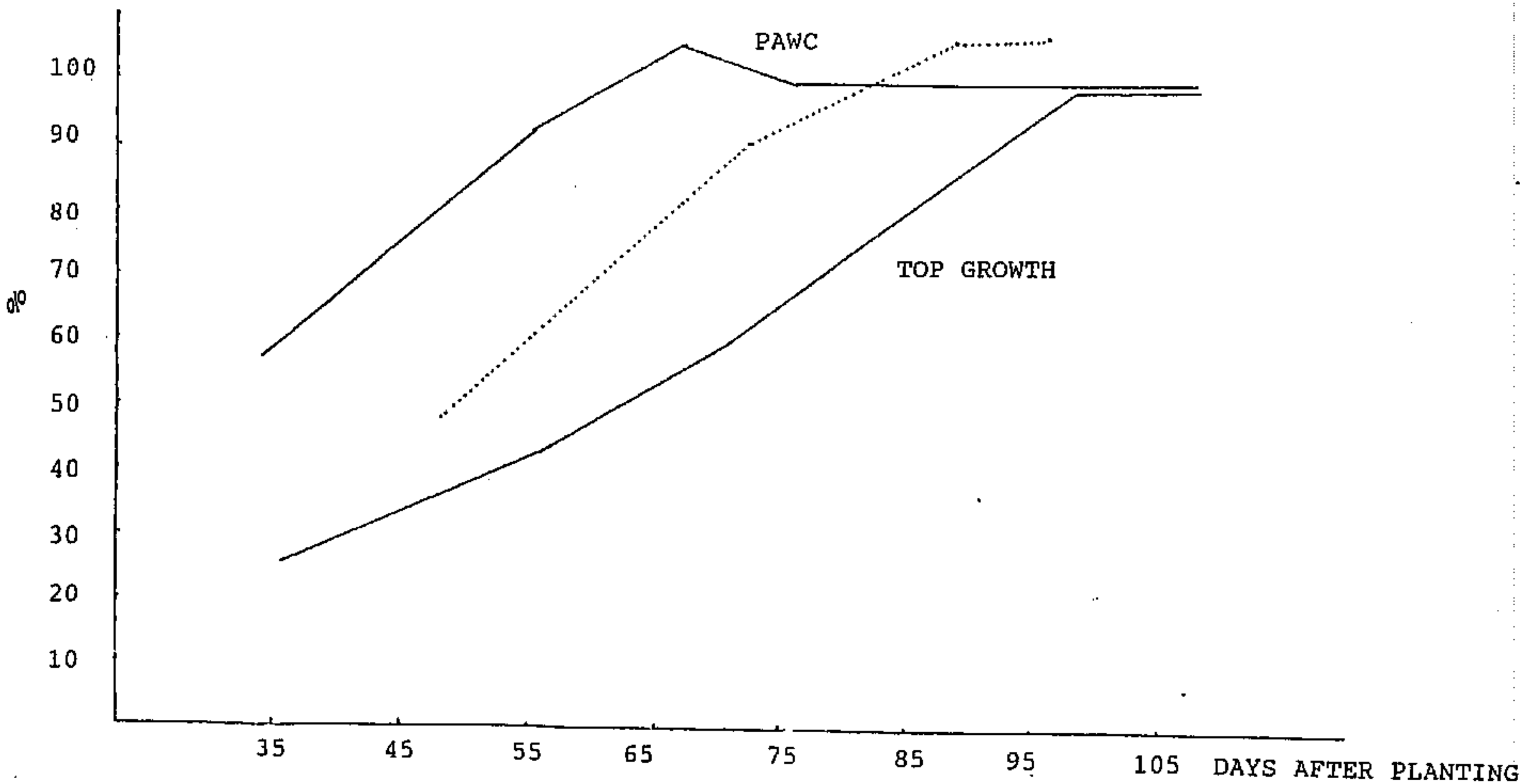


FIG.3.11 RELATIVE PAWC AND RELATIVE TOP GROWTH OF WHEAT AT SITE D12 (1985 SEASON)

TABLE 3.5 - Quantities of soil water extracted by wheat at different soil depths and PAWC values for each growth stage at site D12 (1985 season)

	water extracted (mm).				
depth (mm)	a	b	c	d	flowering
0- 100	13,0	15,0	15,8	15,0	14,8
100- 200	11,6	14,3	15,0	14,8	15,0
200- 300	10,0	14,0	15,7	15,5	15,5
300- 400	7,3	11,8	13,3	13,5	15,5
400- 500	6,0	11,8	13,5	12,8	14,5
500- 600	6,3	13,5	15,7	14,0	12,5
600- 700	5,7	15,7	16,8	15,0	12,3
700- 800	3,3	14,0	16,7	15,0	12,2
800- 900	1,3	8,0	16,0	14,5	12,3
900-1000		6,2	6,0	8,5	9,2
1000-1100		3,5	2,7	3,5	4,5
1100-1200					1,5
1200-1300					
PAWC	64,5	127,8	147,8	142,1	139,8

3.2.1.2 Winter 1986

3.2.1.2.1 Stem elongation and pre-dawn leaf water potential patterns

On plot D6a the growth of the plants was similar to the growth observed on control plot e during the first 28 days of the drying cycle (Figure 3.12). The growth rate on plot D6a decreased sharply on the 29th day of the drying cycle and reached a minimum value of 3mm per day nine days later (Figure 3.13). However, at this time the plants were already experiencing severe water stress. The growth rate on plot D6a started decreasing relative to

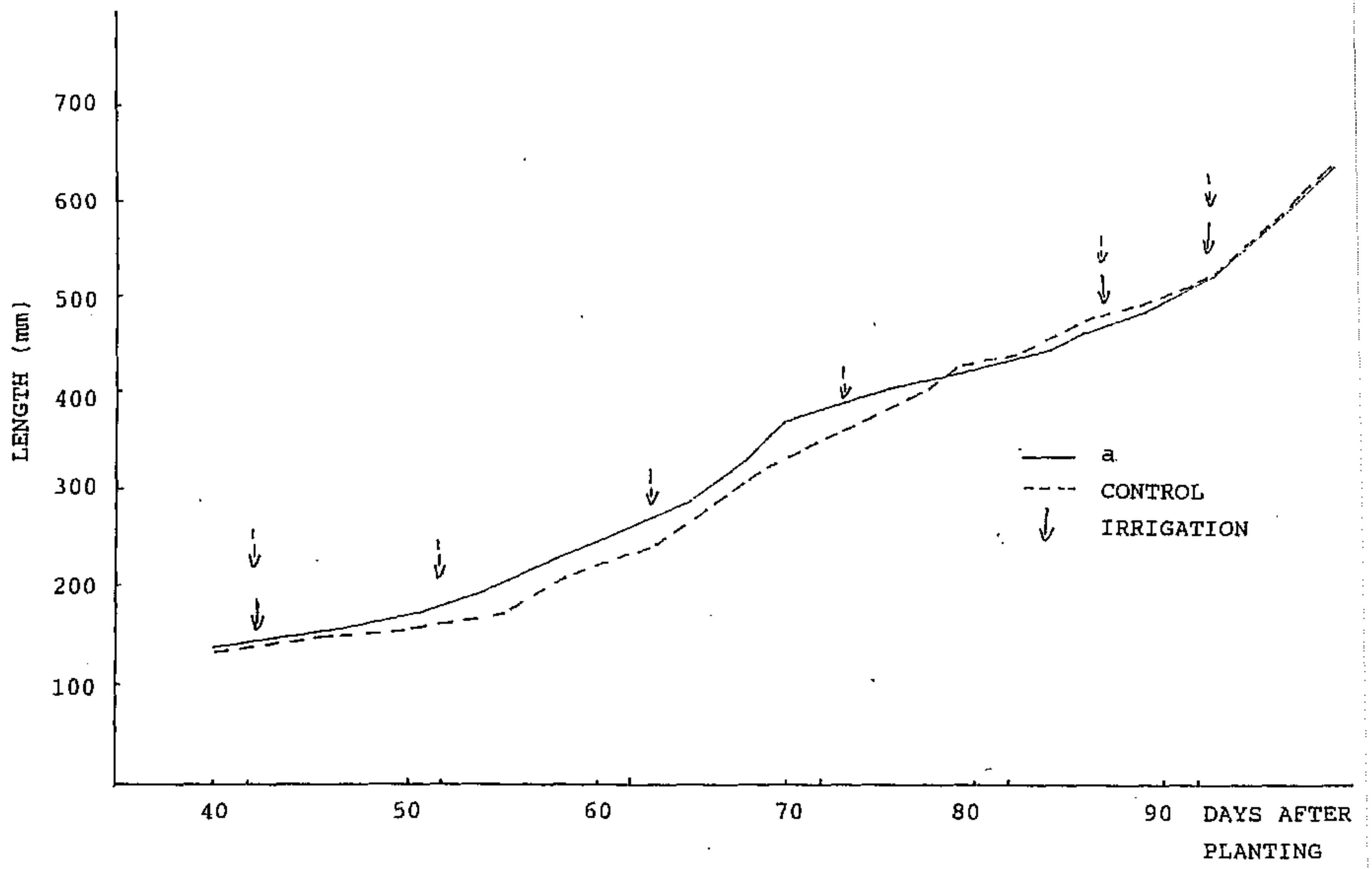


FIG.3.12 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D6a (1986 SEASON)

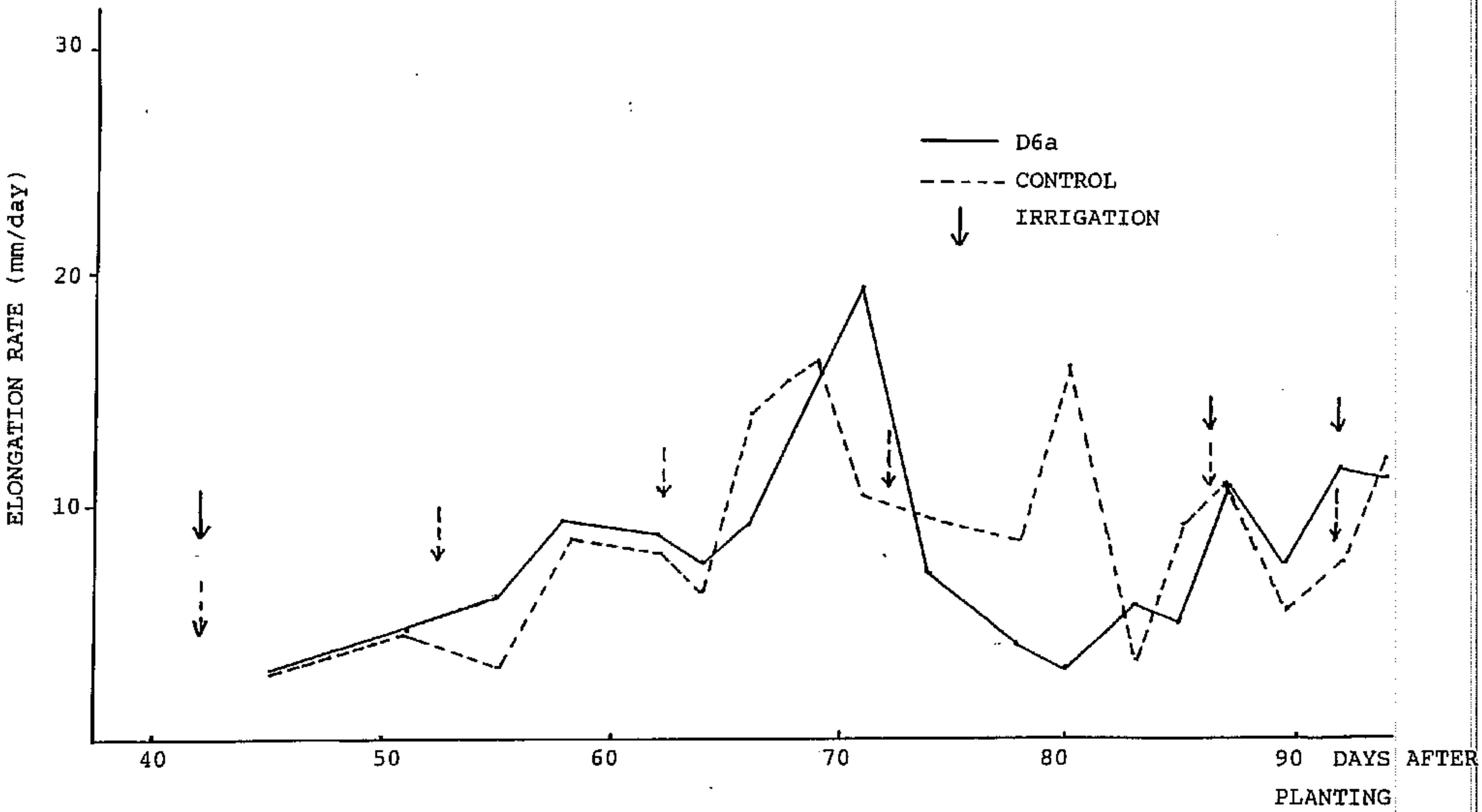


FIG. 3.13 STEM ELONGATION RATE OF WHEAT ON PLOT D6a (1986 SEASON)

that of the control plot on day 16 of the drying cycle (i.e. day 58 after planting) to reach a minimum valueon day 22 of the drying cycle (i.e. day 64 after planting). Then a large increase in growth rate was measured from day 24 until day 29 (Figure 3.13). This sudden increase was possibly caused by a drop in maximum air temperature from 28°C (on day 65 after planting) to 13,2°C (on day 71 after planting) which resulted in a much lower evaporative demand (from 5,5mm to 1,5mm) and a temporary relief of stress. The fact that plot D6a responded better to the temperature decrease than the control plot can be explained by a better developed root system on plot D6a as a result of withholding irrigation at a very young growth stage. The onset of FMS on day 22 is supported by the PLWP pattern (Figure 3.14). PLWP started decreasing on day 16 of the drying cycle and reached a minimum value of -950kPa on day 23. As a result of the drop in air temperature, PLWP increased to above -500kPa. This is similar to the increase in growth rate measured during that period. After reaching a maximum value (-400kPa) on day 29 of the drying cycle, PLWP dropped again and continued the fluctuating phase which started on day 21 of the drying cycle. The slight decrease in PLWP on day 13 was the result of an increase in maximum air temperature from 19,4 °C to 26,5 °C on days 8 and 11 respectively. After the drop in PLWP on day 30 of the

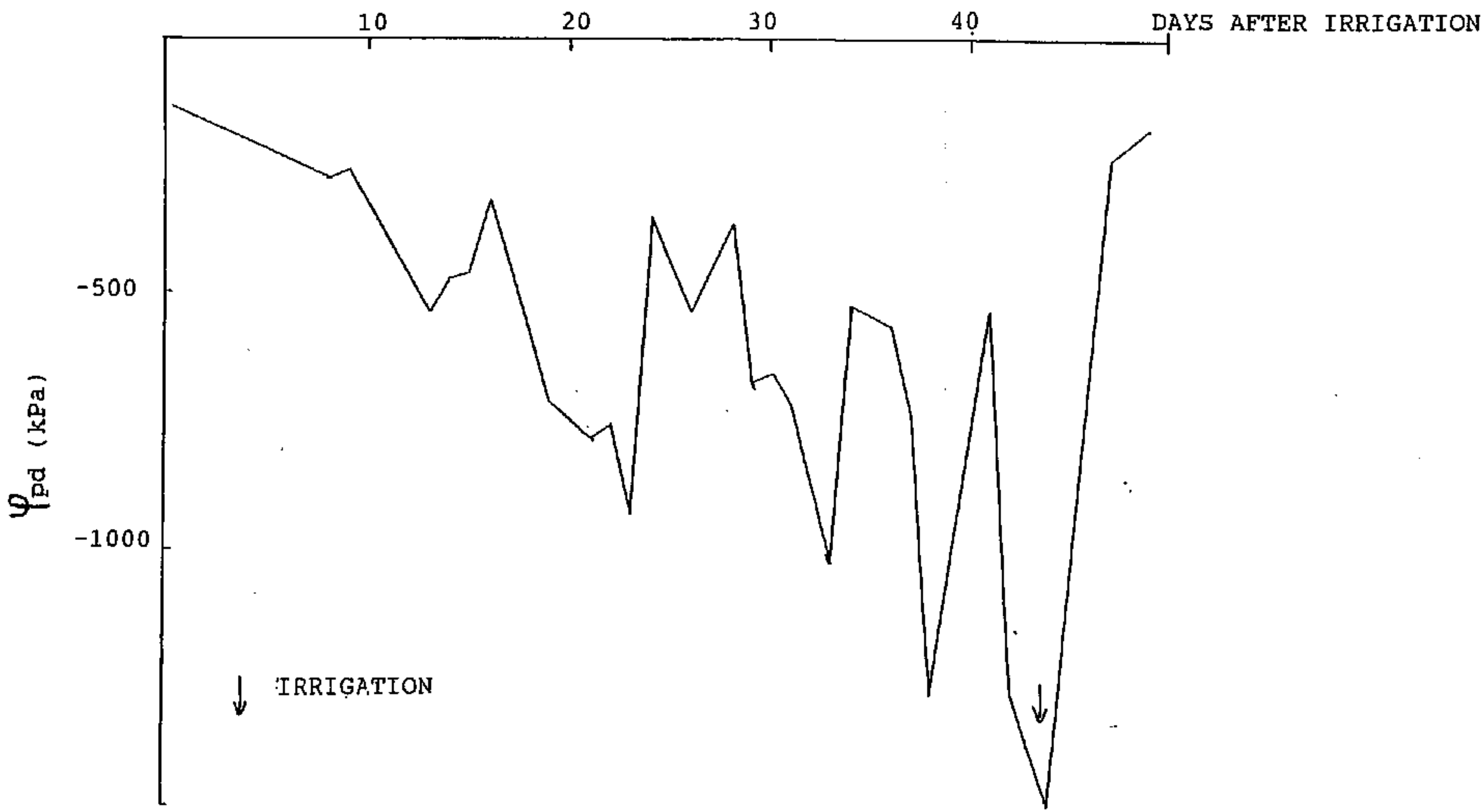


FIG.3.14 PRE-DAWN LEAF WATER POTENTIAL OF WHEAT ON PLOT D6a (1986 SEASON)

drying cycle, the pattern shows a very strong fluctuating phase. The values went up and down in such a way that the next minimum was smaller than the previous one and always below -1000kPa, while the maximum values nearly reached -500kPa. This period was characterized by a steep increase in temperature (from 23,2°C on day 34 to 30,5°C on day 37).

Similar results were obtained on plot D12a. The stem elongation patterns of plot D12a are given in Appendices 3.1.4 and 3.1.5. The elongation rate pattern was similar to that of plot D6a. However, the increase in elongation rate from day 23 until day 29 (day 65 until day 71 after planting) was not as high as on plot D6a and was followed by a short increase from day 32 until day 36 (day 74 until day 78 after planting). The PLWP patterns for plots D6a and D12a were practically identical except for the higher PLWP values at the end of the drying cycle and the smaller differences in minimum and maximum values during the fluctuation phase in the case of D12a (Figure 3.14 and Appendix 3.2.4).

The results obtained on plot D16a were similar to those of plots D6a and D12a. However, the stem elongation rate pattern for plot D16a reached a minimum value on day 24 (before increasing again due to the decrease in temperature) which was two days later than on plots D6a and D12a (Appendix 3.1.7). The PLWP pattern for plot D16a was practically identical to the patterns for plot D6a and D12a. The influence of climatic factors (temperature, evaporative demand) on the PLWP pattern was clearly illustrated again, especially when temperatures temporarily decreased after day 22 of the drying cycle (Appendix 3.2.5).

Compared to the results found during the 1985 winter season, the period to reach FMS on plots D6a and D12a was nine days longer during this season. Contradictory to the 1985 results, plants did not go into dormancy (zero growth) during the 1986 season. The experiments were started later during the 1985 season and temperatures were markedly higher (ranging from 25 °C to 30 °C during the first 25 days of the drying cycle) than during the 1986 season. The PLWP patterns for plots D6a and D12a for the 1986 season were also different from those for the 1985 season. In 1986 a gradual fluctuating decrease in PLWP during the drying cycle was found opposed to the distinct steps found in 1985. Average PLWP values from day 13 until day 23 of the drying cycle were similar for both seasons (-600kPa).

Plots D6a, D12a and D16a were irrigated again on day 44 of the drying cycle and PLWP immediately increased to -200kPa on all three plots. This was similar to the results found during the 1985 winter season. Stem elongation rates, however, responded differently. On plot D6a stem elongation rates exceeded those of the control plot as during the 1985 season. The rates on plot D12a exceeded those on the control plot only after the second irrigation on day 50 of the drying cycle. Finally, the elongation rates on plot D16a never exceeded those on the control plot, even after the second irrigation. At the end of the growing season, the plants on plots D6a, D12a and D16a had the same height as on the respective control plots (Figure 3.12 and Appendices 3.1.4 and 3.1.6).

The strongly fluctuating nature of the stem elongation rate pattern for plot D6b made it very difficult to identify the onset of FMS (Figure 3.16). On day 26 of the drying cycle (day 78 after planting) the stem elongation rate on plot D6b dropped sharply, but quickly recovered again to equal that of the control plot. This period of recovery was characterized by a sharp drop in maximum air temperature from 30,5 °C on day 78 to 22°C on day 81. However, minimum air temperatures also dropped very sharply from 17 °C on day 80 to -1°C on day 82 after planting. This explains the drop in elongation rate on

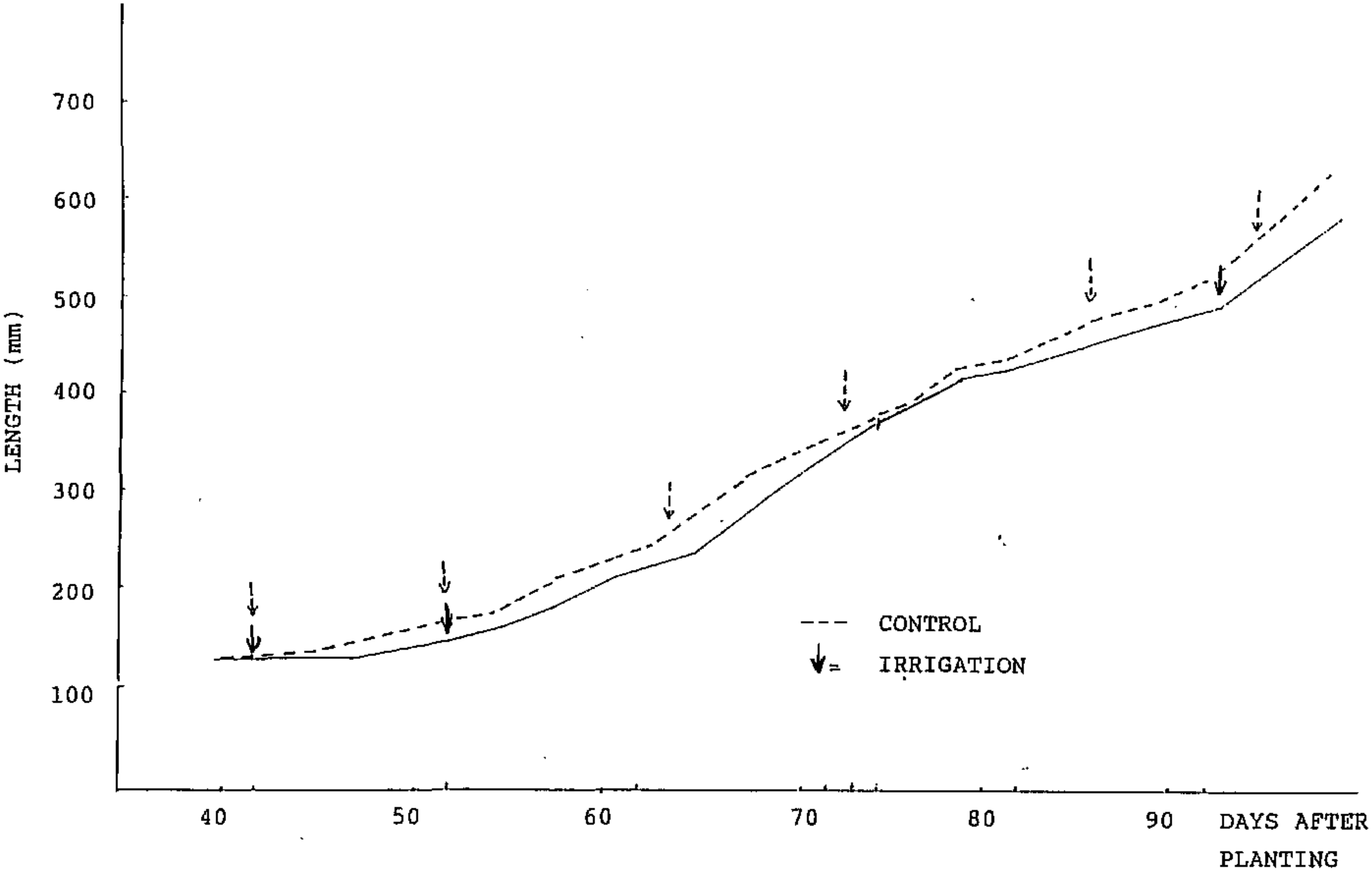


FIG.3.15 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D6b (1986 SEASON)

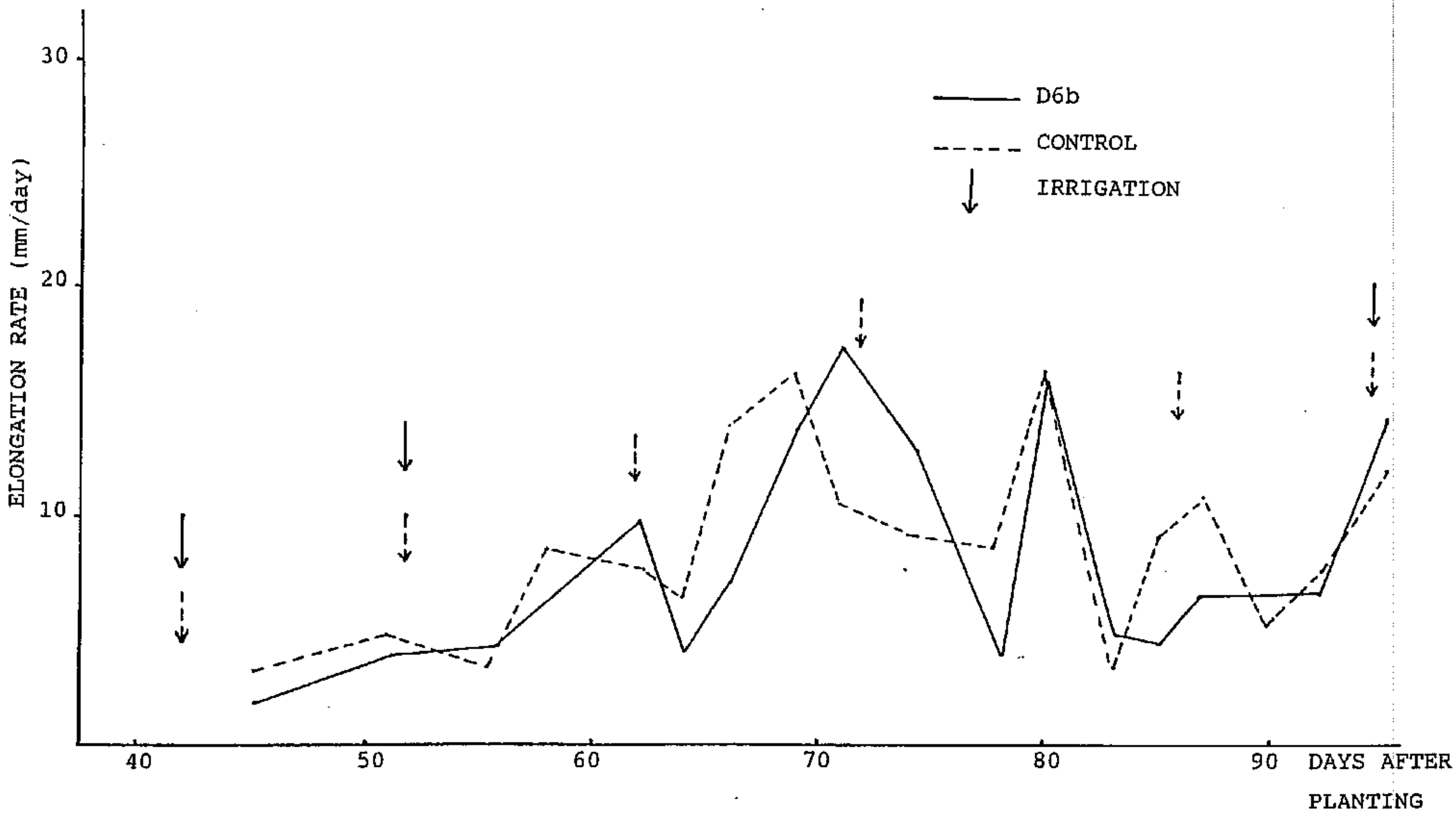


FIG. 3.16 STEM ELONGATION RATE OF WHEAT ON PLOT D6b (1986 SEASON)

the control plot. The control plot partially recovered quickly during the subsequent days which were characterized by higher minimum air temperatures (between 3.5 °C and 12.5 °C). The elongation rates on plot D6b remained low until it was irrigated again. This clearly indicates that soil-induced water stress prevailed in plot D6b by day 26 (day 78 after planting). PLWP remained high (above -250kPa) for the first ten days of the drying cycle and then fluctuated at an average of just over -500kPa until day 26 (Figure 3.17). The low value measured on day 14 was the result of a sharp increase in air temperature from 14,5°C to 28°C (on days 9 and 13 of the drying cycle), whereafter temperatures decreased again. After day 26 it dropped sharply and started to fluctuate strongly with low, gradually decreasing minima. In accordance with results from previous studies and the stem elongation data day 26 is, therefore, clearly the day on which FMS set in.

The stem elongation rate pattern found on plot D12b very clearly showed the onset of FMS. The rate dropped relative to that of the control plot on the 26th day after the start of the drying cycle and remained low (Appendix 3.1.9). As in the case of D6b, PLWP remained high for the first few days of the drying cycle and then remained just over -500kPa until day 26, after which it

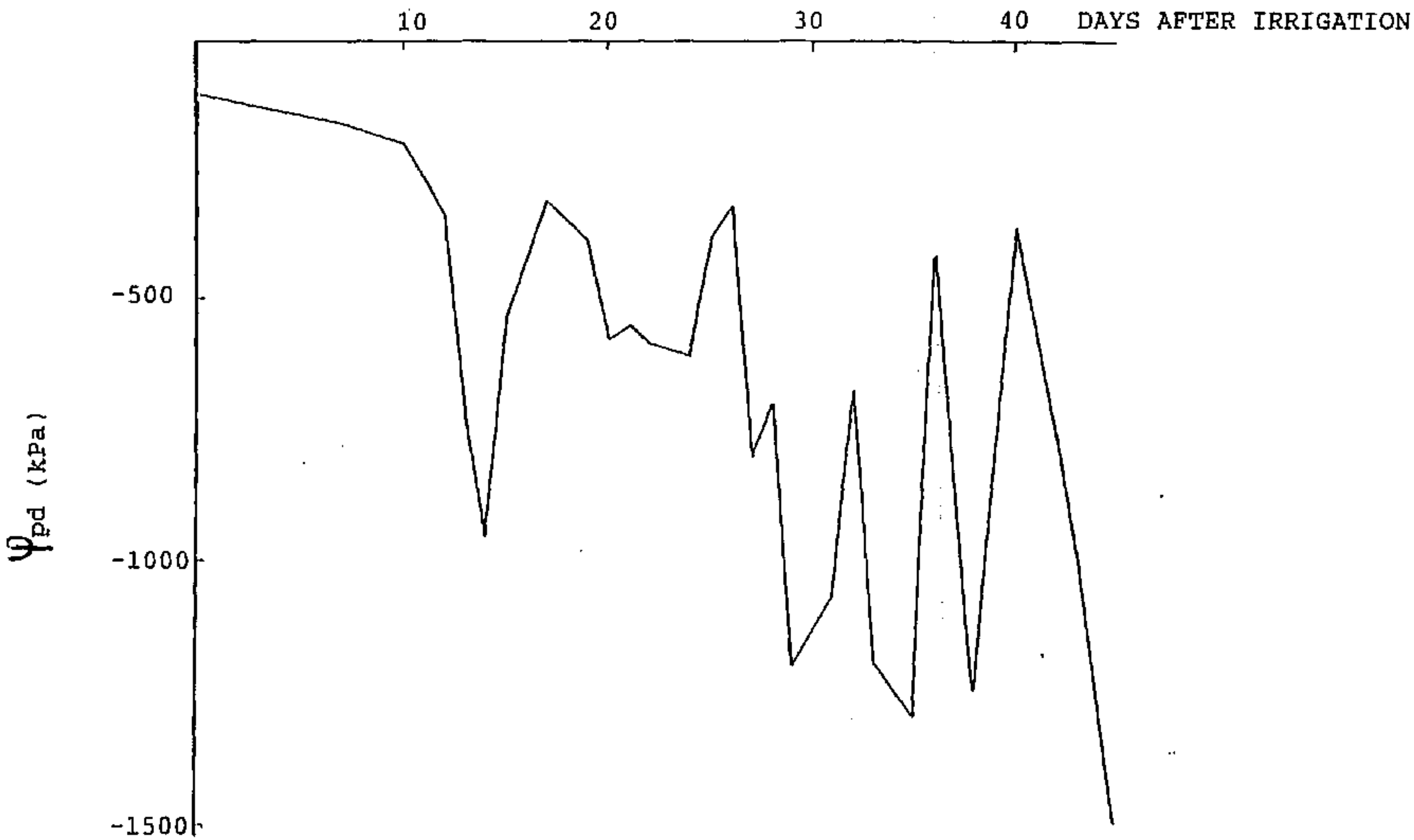


FIG.3.17. PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D6b (1986 SEASON)

dropped sharply to low minima during a fluctuating phase (Appendix 3.2.6).

As in the case of D6b and D12b the stem elongation rate of the plants on plot D16b showed a sharp decrease on day 26 of the drying cycle (appendix 3.1.11). As in the case of D6b it quickly recovered. It followed the pattern of the control plot thereafter. Stem elongation rate, therefore, did not give a clear indication of the onset of soil-induced water stress. As in the case of D6b and D12b PLWP remained high for about the first ten days of the drying cycle and then dropped to a plateau around -500kPa until day 26, after which it dropped sharply to very low values (Appendix 3.2.7). This seems to be a clear indication of the onset of FMS.

The b plots were irrigated again on day 40 of the drying cycle. PLWP increased to about -400kPa but then dropped again. As in the case of the a-plots only the elongation rate of plot D6b exceeded that of the control plot. At the end of the growing season, the plants on plots D6b, D12b and D16b were shorter (from 70mm on D6b to 150mm on D16b and 180mm on D12b) than those on the respective control plots (Figure 3.15 and Appendices 3.1.8 and 3.1.10).

The stem elongation on plot D6c was smaller than that on control plot D6e throughout the whole season. Twenty days after the start of the drying cycle, the gap between the cumulative elongation lines started to widen as the growth rate on plot D6c started decreasing (Figures 3.18 and 3.19). After this drop, the elongation rate on plot D6c partially recovered, but then decreased again and remained smaller than the rate measured on the control plot (Figure 3.19). The PLWP pattern for plot D6c showed the onset of FMS very clearly. On day 21 of the drying cycle, PLWP dropped very sharply to -1200kPa, after which the values started fluctuating with decreasing minima (Figure 3.20).

The stem elongation rate pattern for plot D12c was so variable that it could not be used to identify FMS (Appendix 3.1.13). It often dropped below the values for the control plot even while plot D12c was well-watered (days 50 to 75 after planting). Even after the sharp drop on day 92 it increased again to values equalling those of the control plot. The PLWP pattern for D12c indicated day 21 as the day after which stress set in, by a drop in PLWP values (Appendix 3.2.8). The subsequent fluctuating phase did not have the clearly decreasing minima of the other stressed plots.

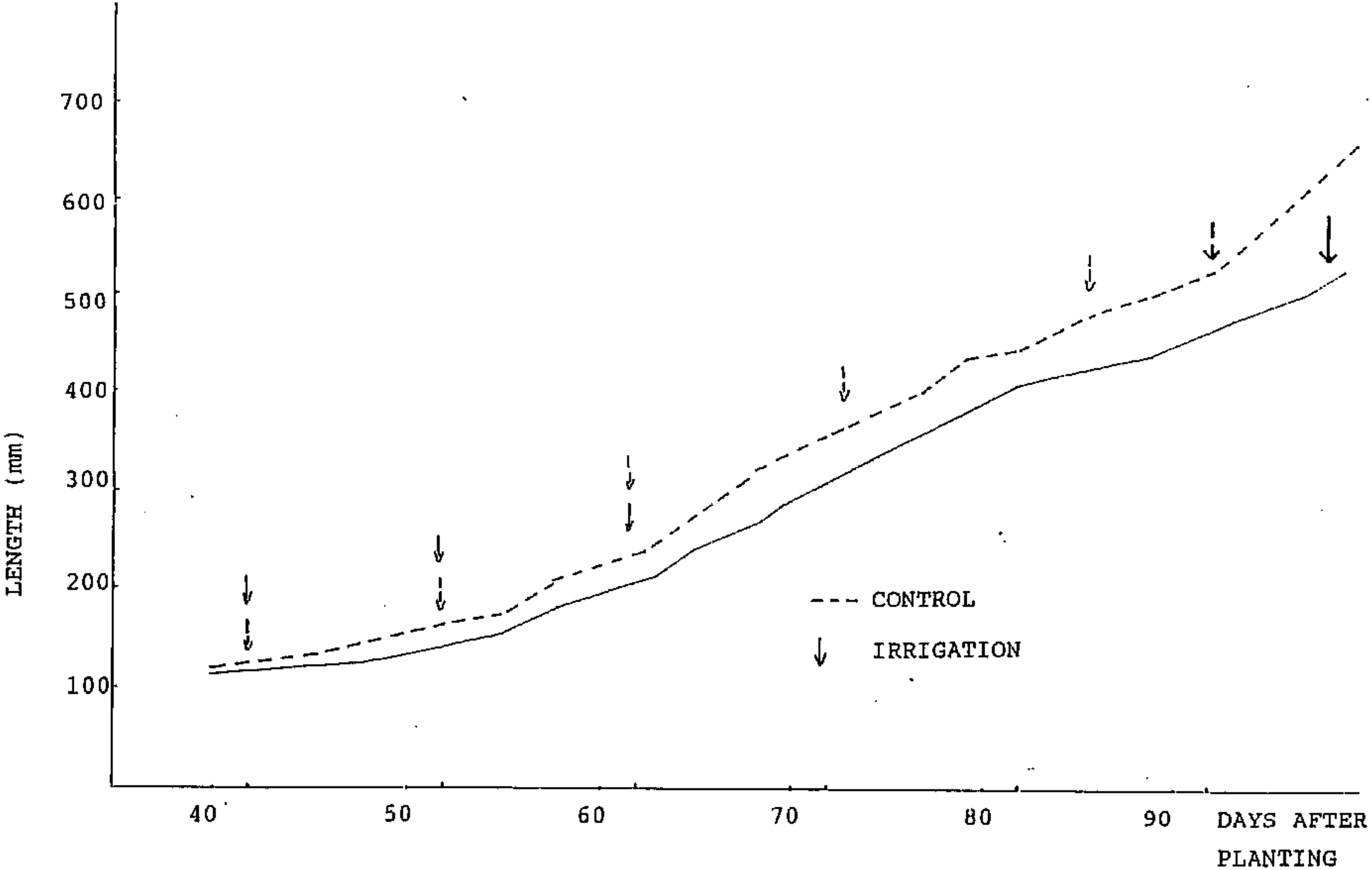


FIG.3.18. CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D6c (1986 SEASON)

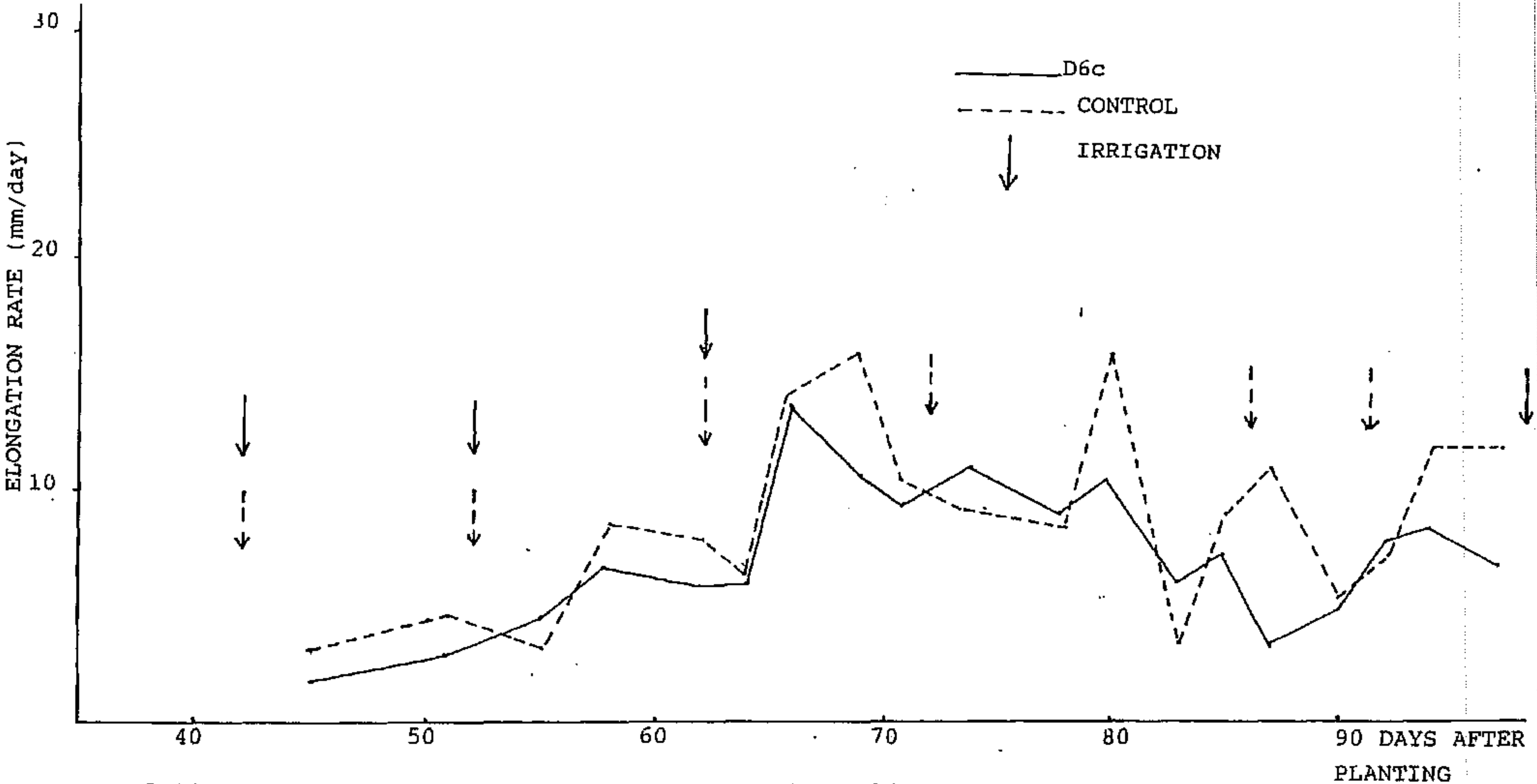


FIG. 3.19 STEM ELONGATION RATE OF WHEAT ON PLOT D6c (1986 SEASON)

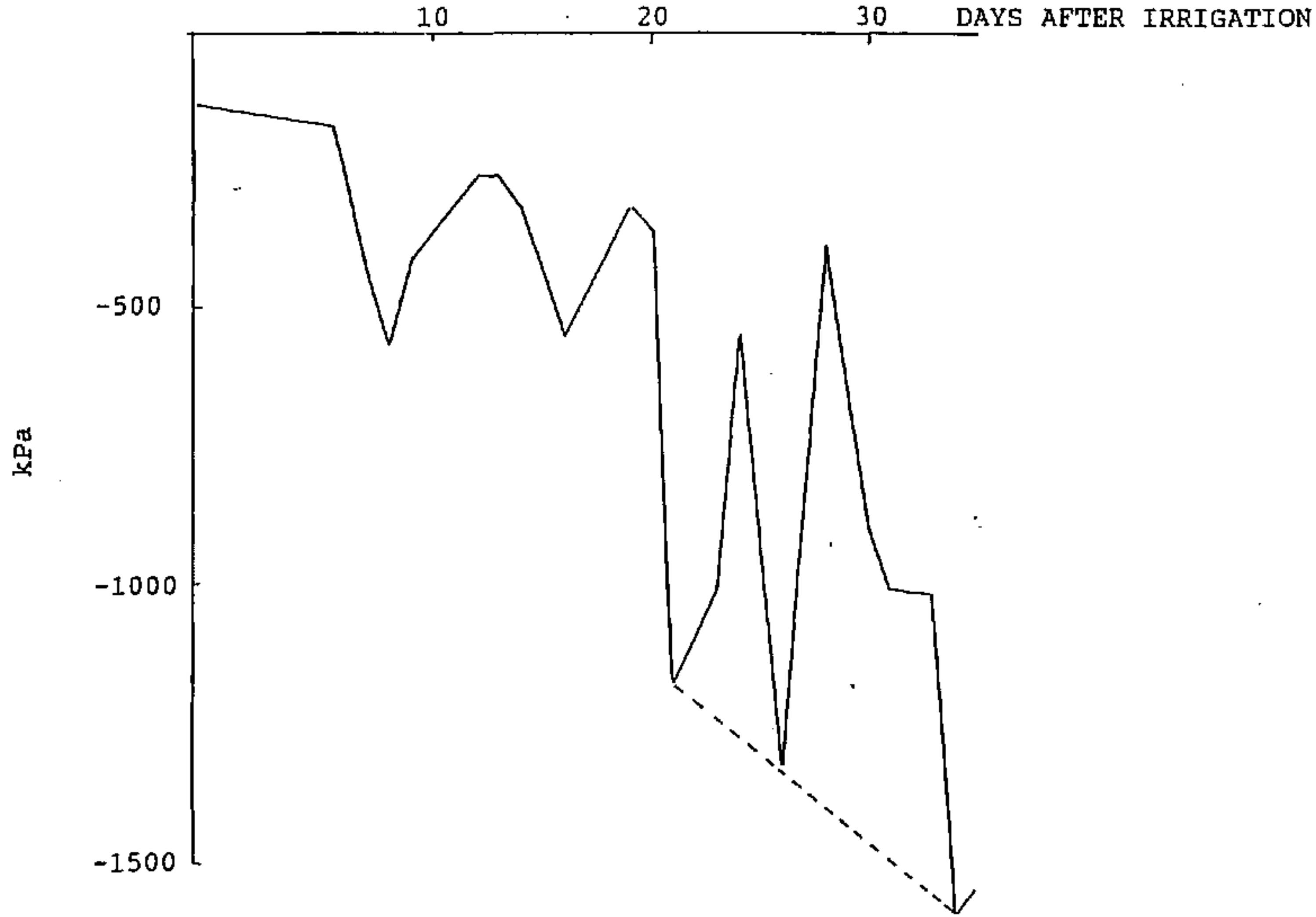


FIG.3.20 PRE-DAWN LEAFWATER POTENTIAL PATTERN OF WHEAT ON PLOT D6c. (1986 SEASON)

As in the case of D12c the stem elongation rate pattern for plot D16c was so variable that it could not be used to identify the onset of stress. After day 87 (day 25 of the drying cycle) it appears to decrease clearly relative to the control, but even then it recovered a few days later (Appendix 3.1.15). PLWP clearly indicated the onset of FMS. The values dropped sharply 21 days after the start of the drying cycle and stayed below -1200kPa for the next three days (Appendix 3.2.9).

The plots were irrigated again 15 days after the onset of FMS (i.e. day 98 after planting). At the end of the growing season the plants on plots D6c, D12c and D16c were shorter (90mm to 140mm) than those on the respective control plots (Figure 3.18 and Appendices 3.1.12 and 3.1.14).

The stem elongation pattern found on plot D6d was similar to that found on control plot D6e and the difference in height at the end of the experiments was small (Figure 3.21). The stem elongation rate pattern could not indicate the onset of FMS (Figure 3.22). The PLWP pattern showed a drop twelve days after the start of the drying cycle. This drop was the result of the "greenhouse" effect induced by the plastic covers for protection against rain. The high temperatures under the plastic

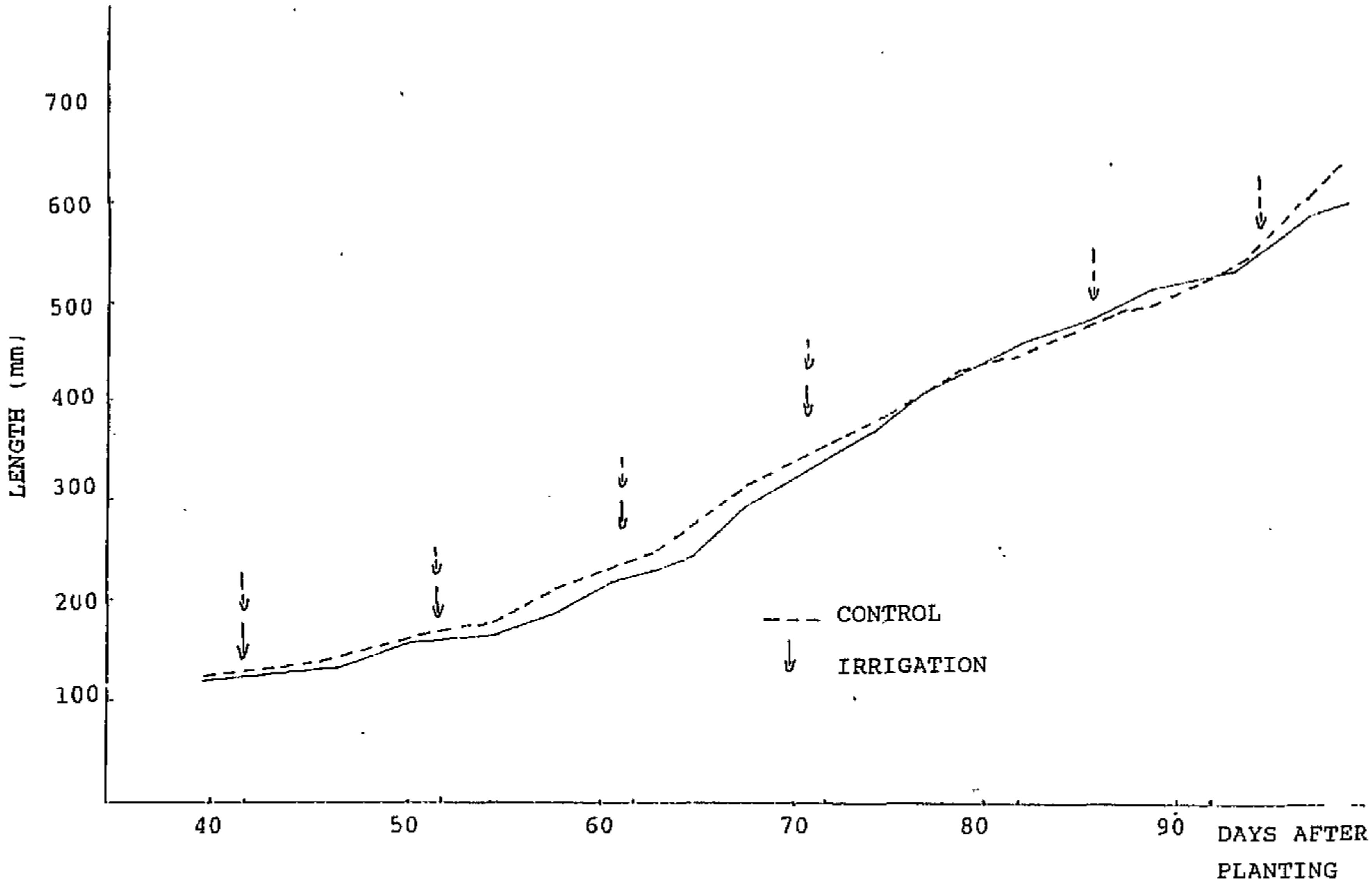


FIG. 3.21 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D6d (1986 SEASON)

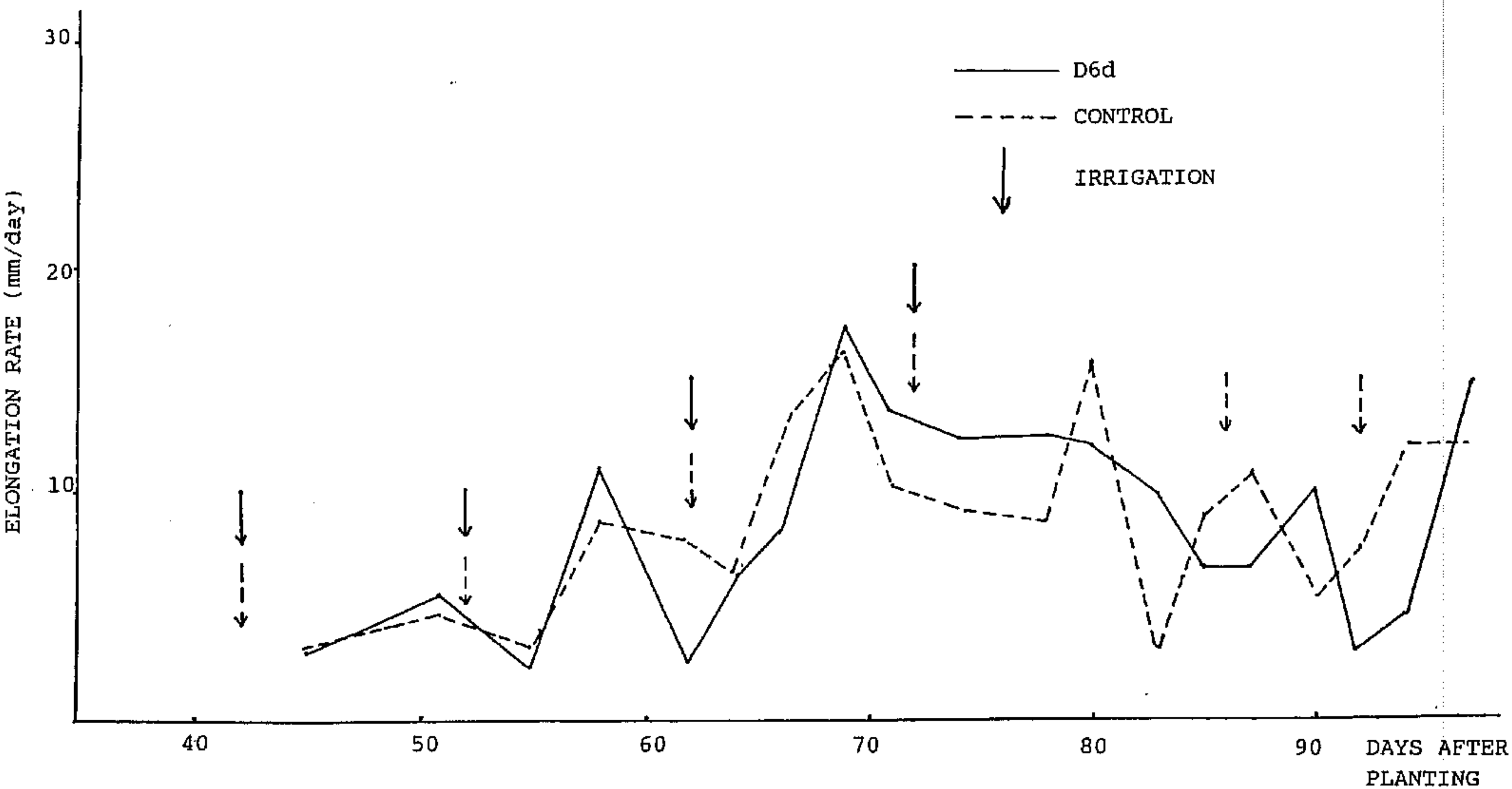


FIG. 3.22 STEM ELONGATION RATE OF WHEAT ON PLOT D6d (1986 SEASON)

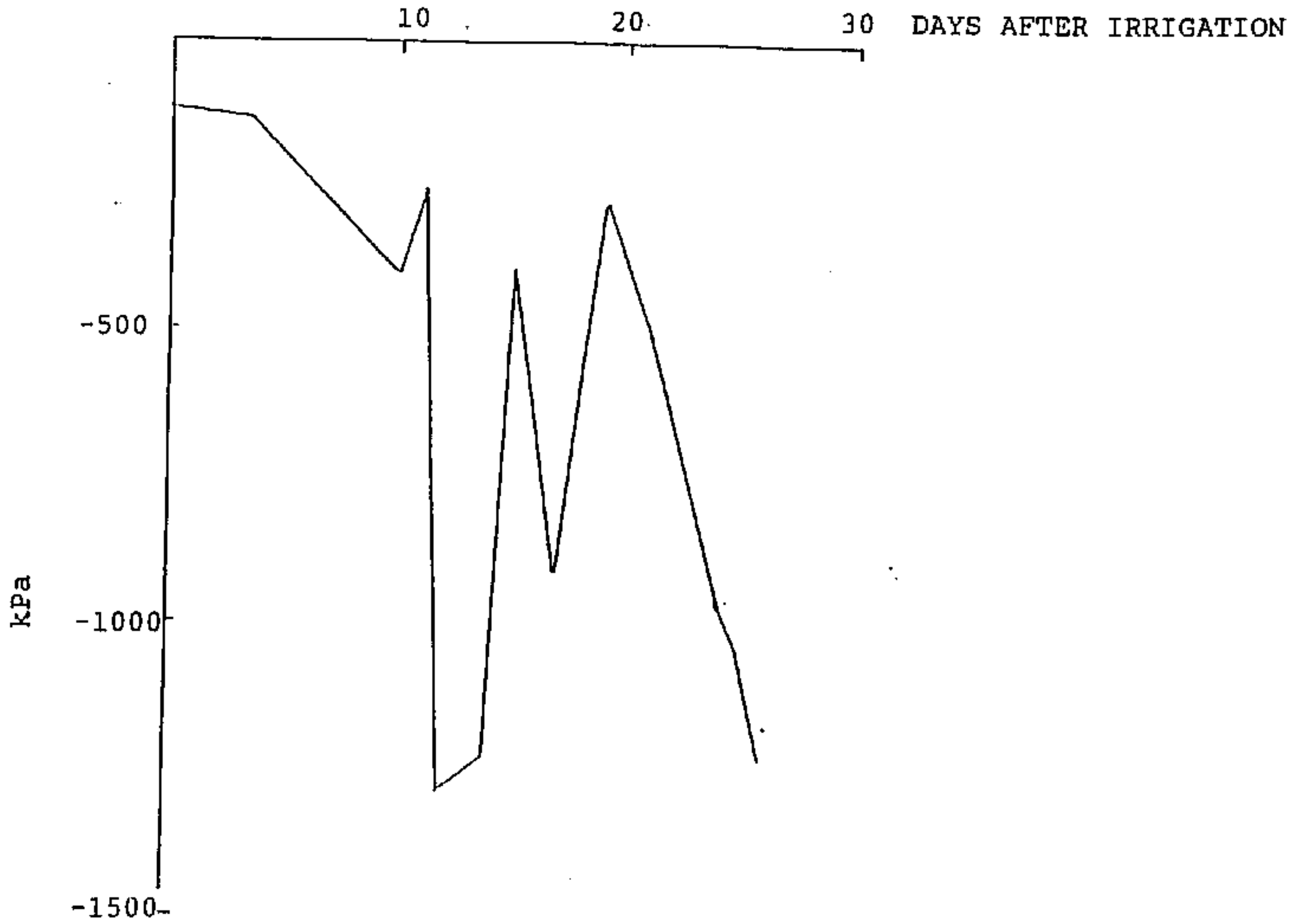


FIG.3.23 PRE-DAWN LEAFWATER POTENTIAL PATTERN OF WHEAT ON PLOT D6d (1986 SEASON)

covers induced temporary stress conditions. FMS was identified when PLWP dropped below -1200kPa 25 days after the start of the drying cycle (Figure 3.23).

Stem elongation rate on plot D12d could not be used to identify FMS since it did not decrease relative to the control plot (Appendix 3.1.17). FMS could be detected from the drop in PLWP which started on day 19 of the drying cycle (Appendix 3.2.10). The previous drop in PLWP (day 12) was caused by the "greenhouse" effect. This was confirmed by similar low PLWP values at sites D6 and D16 on this day.

The stem elongation patterns for plots D16d and D16e were similar until day 19 of the drying cycle but soil water stress had little effect on the final height of the plants on plot D12d (Appendix 3.1.18). FMS could not clearly be identified from stem elongation rates, although these rates did become lower for D16d than for D16e from 20 days after the start of the drying cycle on D16d (Appendix 3.1.19). The onset of FMS on day 24 was indicated by the drop in PLWP which started on day 19 of the drying cycle. PLWP did not fall as sharply as during the previous drying cycles, but was decreasing continuously over a period of three days without any recovery (Appendix 3.2.11). The latter was similar to the

TABLE 3.6 - Phenological stages at the start and end of the drying cycles, number of days to reach FMS and parameters used to identify FMS of wheat at different growth stages at sites D6, D12 and D16 (1986 season)

Plot no.	Phenological stage * start	end	Days to FMS	Parameters **
D6a	3	7	22	PLWP* and SER
D6b	5	8-9	26	PLWP and SER
D6c	7	9	21	PLWP and SER
D6d	8	10	25	PLWP
D12a	3	7	22	PLWP* and SER
D12b	5	8-9	27	PLWP and SER
D12c	7	9	21	PLWP
D12d	8	10	25	PLWP
D16a	3	7	22	PLWP* and SER
D16b	5	8-9	27	PLWP and SER
D16c	7	9	21	PLWP
D16d	8	10		

* Phenological stages:
Stage 3: Tillering.
Stage 5: Leaf sheaths strongly erected.
Stage 7: First node of stem visible.
Stage 8: Flag leaf just visible.
Stage 9: Flag leaf fully developed.
Stage 10: Ears in boot.

** Parameters:
PLWP : Pre-dawn leaf water potential.
PLWP*: At values higher than -1000kPa
SER : Stem elongation rate.

pattern found on plot D12d, and somewhat similar to the pattern on D16d.

The plots were irrigated again on day 103 after planting (i.e. 7 days after the onset of FMS). Only small differences in total height of the plants (50mm averagely) were measured at the end of the growing season.

The number of days to reach FMS, the phenological stages at the start and the end of the drying cycle and the parameters used to identify FMS are summarized in Table 3.6.

3.2.1.2.2 PAWC values and soil water extraction patterns

The soil water extraction patterns for the different growth stages at site D6 are shown in Figure 3.24. The patterns were basically identical to those found during the 1985 winter season. They had the same basic fan shape and their evolution consisted mainly in the downward movement of the convergence point from a depth of 700mm at stage a to a depth of 1100mm at stage d. The plants extracted water mainly from soil layers up to a depth of 600mm. The reason for this is the compacted B horizon which made the development and penetration of the roots

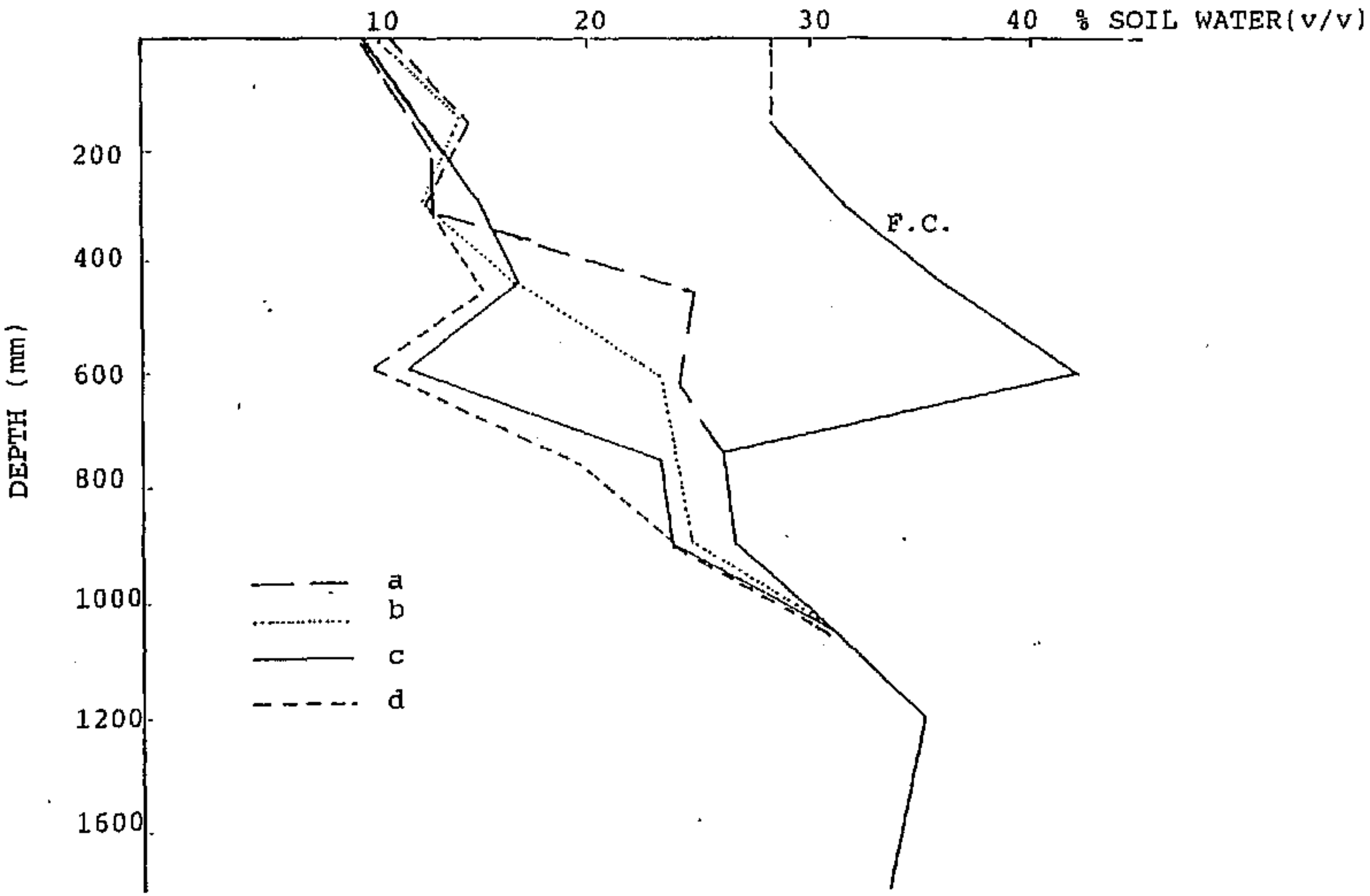


FIG.3.24 SOIL WATER EXTRACTION PATTERNS OF WHEAT AT FIRST MATERIAL STRESS AT DIFFERENT GROWTH STAGES AT SITE D6 (1986 SEASON)

very difficult. The quantities of soil water extracted at different soil depths and the PAWC values for each growth stage are listed in Table 3.7. Soil water extraction did not increase much below a depth of 700mm. The difference between stage a and stage d was only 8.5mm which is less than 6% of the total extraction and less than 20% of the difference between the PAWC at growth stage a and the PAWC at growth stage d. This means that 80% of this difference is caused by a higher soil water extraction in the upper soil layers (above 600mm). These results were also found during the 1985 winter experiments (See paragraph 3.2.1.1.2). PAWC values were comparable to those obtained during the 1985 winter experiments (Compare Tables 3.4 and 3.7). Relative PAWC values and relative top growth at the different growth stages are shown in Figure 3.25. The maximum PAWC value was reached at growth stage c.

The soil water extraction patterns for each growth stage at site D12 are presented in Appendix 3.3.3. The basic shape of the patterns was more or less the same as that found during the 1985 winter experiments (Appendix 3.3.1). The difference for stage a was the deeper rooting depth during the 1986 season. A possible reason for this was the fact that the plots were at field capacity level before planting which was not the case during the 1985

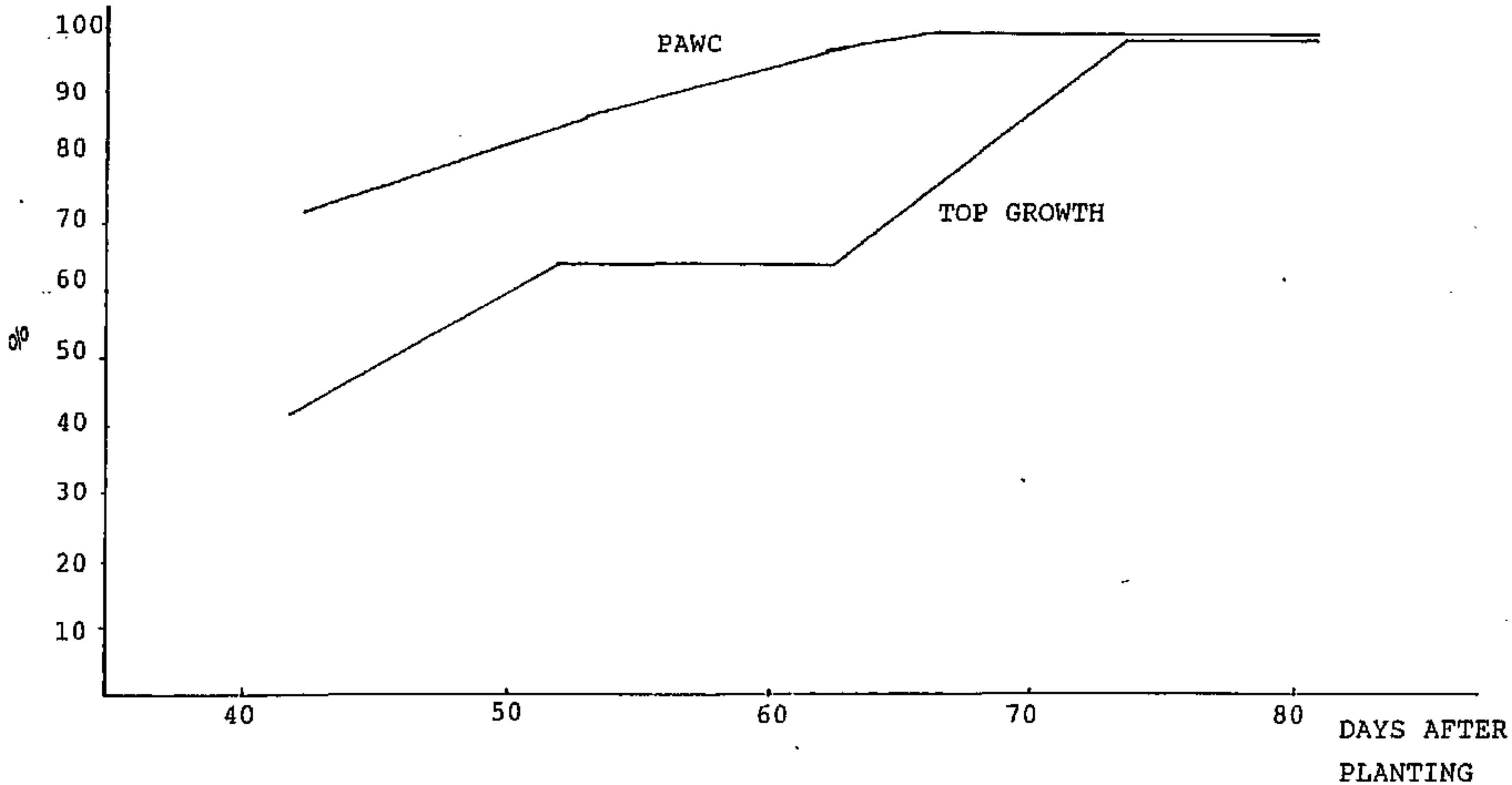


FIG.3.25 RELATIVE PAWC AND RELATIVE TOP GROWTH OF WHEAT AT SITE D6 (1986 SEASON)

winter season. At the other growth stages a smaller extraction from soil layers between 600mm and 900mm depth was measured during 1986 than during 1985 (compare Tables 3.5 and 3.8). This was somewhat compensated by a higher extraction from layers in the upper part of the profile, but the total extraction (i.e. PAWC values) was smaller during 1986 than during the previous season. The reason for this may be an overestimation of PAWC during the 1985 season. The extraction figures found in the deeper soil layers (1985 season) may also reflect the soil water deficit before the start of the experiments. There was a very small difference between the extraction patterns (and PAWC values) found during stages a and b. At stage c the extraction from layers deeper in the profile increased slightly relative to stage b while the extraction in the upper part was the same as at stage b. Going from stage c to stage d, the plants did not extract more water from layers deeper in the profile but mainly from layers up to a depth of 700mm. The quantities of soil water extracted at different soil depths and the PAWC values for each growth stage are listed in Table 3.8. The relative PAWC values and relative top growth are illustrated in Figure 3.26. The maximum PAWC value was reached at growth stage d.

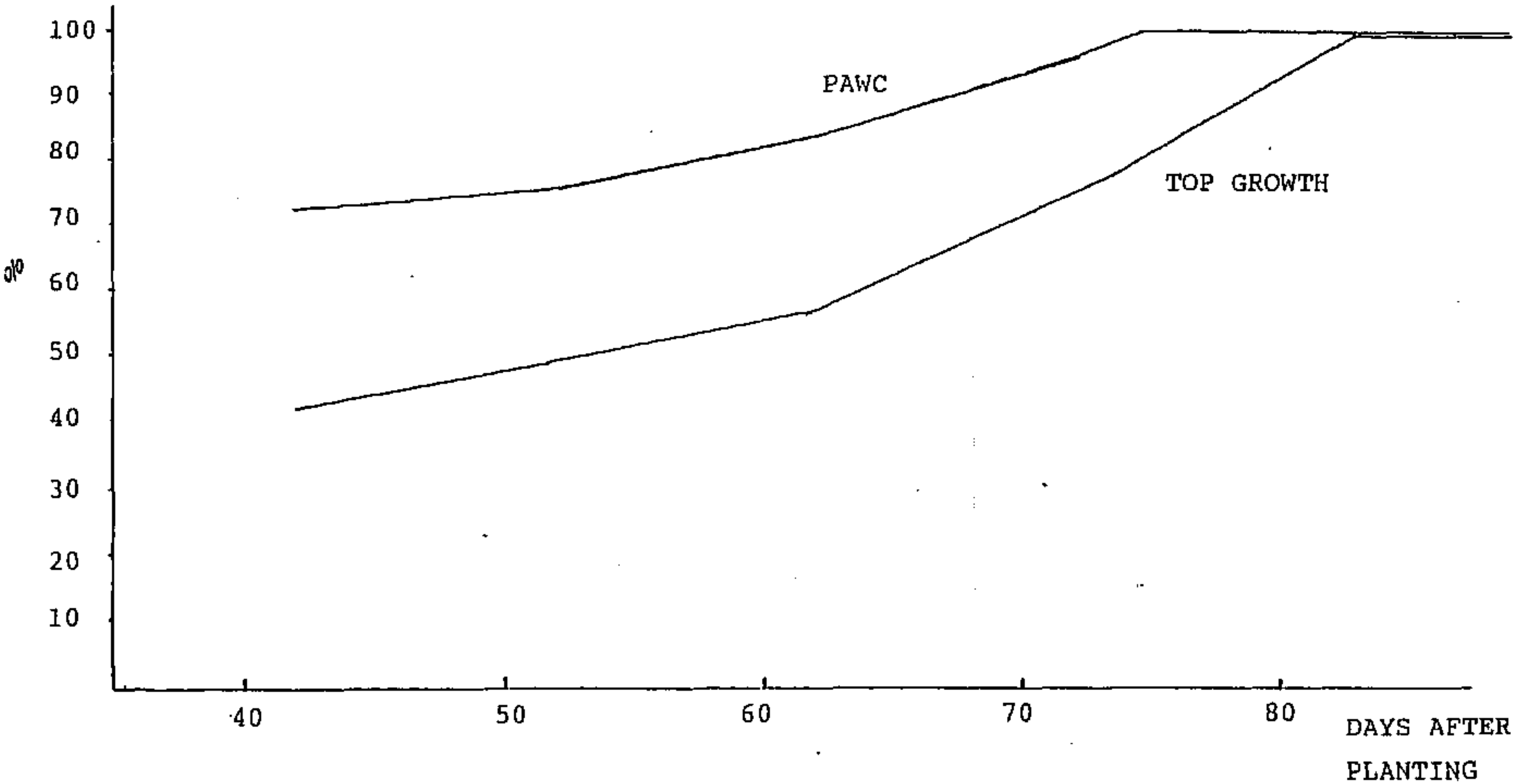


FIG.3.26 RELATIVE PAWC AND RELATIVE TOP GROWTH OF WHEAT AT SITE D12 (1986 SEASON)

TABLE 3.7 - Quantities of soil water extracted by wheat at different soil depths and PAWC values for each growth stage at site D6 (1986 season)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	d
0- 100	16,0	15,3	16,5	14,5
100- 200	16,5	15,7	16,0	15,0
200- 300	18,7	19,2	16,2	18,3
300- 400	13,8	19,3	18,5	19,7
400- 500	13,5	19,0	23,5	24,3
500- 600	18,0	19,2	30,0	31,0
600- 700	5,8	7,3	8,5	14,0
700- 800		2,0	3,0	5,0
800- 900		1,5	3,0	2,5
900-1000			1,0	1,0
1000-1100				
PAWC	102,3	118,5	136,2	145,3

TABLE 3.8 - Quantities of soil water extracted by wheat at different soil depths and PAWC values for each growth stage at site D12 (1986 season)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	d
0- 100	14,5	15,7	14,5	15,3
100- 200	15,3	16,5	15,0	16,5
200- 300	16,0	18,0	17,0	18,5
300- 400	9,5	10,8	10,0	14,5
400- 500	6,3	7,0	7,0	12,0
500- 600	6,8	6,7	7,5	11,3
600- 700	7,8	9,0	8,8	10,5
700- 800	9,0	8,7	9,0	9,0
800- 900	7,5	6,0	7,8	6,8
900-1000	6,0	4,5	8,8	6,5
1000-1100	3,8	3,2	7,2	6,3
1100-1200		1,2	3,5	5,3
1200-1300				
PAWC	102,5	107,3	116,1	132,5

The soil water extraction patterns for each growth stage at site D16 are presented in Appendix 3.3.4. The basic shape of the patterns was very different to those found at sites D6 and D12. Field capacity and first stress lines ran parallel with each other, indicating a more or less constant extraction per unit of depth. At stages a and b the first stress line intersected the field capacity line at a depth of 1350mm, marking the lower boundary of the effective root zone. At stage c this boundary had moved down and first stress and field capacity lines were moving away from each other in this part of the profile. The transition to stage d consisted in a further widening of the gap between first stress and field capacity lines. The quantities of soil water extracted at different soil depths and the PAWC values for each growth stage are listed in Table 3.9. Figure 3.27 illustrates the evolution of relative PAWC and relative top growth at the different growth stages. The maximum PAWC was reached at growth stage d, some time before flowering.

The "parallel line" extraction pattern found at an advanced growth stage (stage d) at site D16 is similar to the patterns found on deep sandy soils at Vaalharts by Boedt & Laker (1985). The "triangular" patterns found at sites D6 and D12 resemble those that Hensley & De Jager

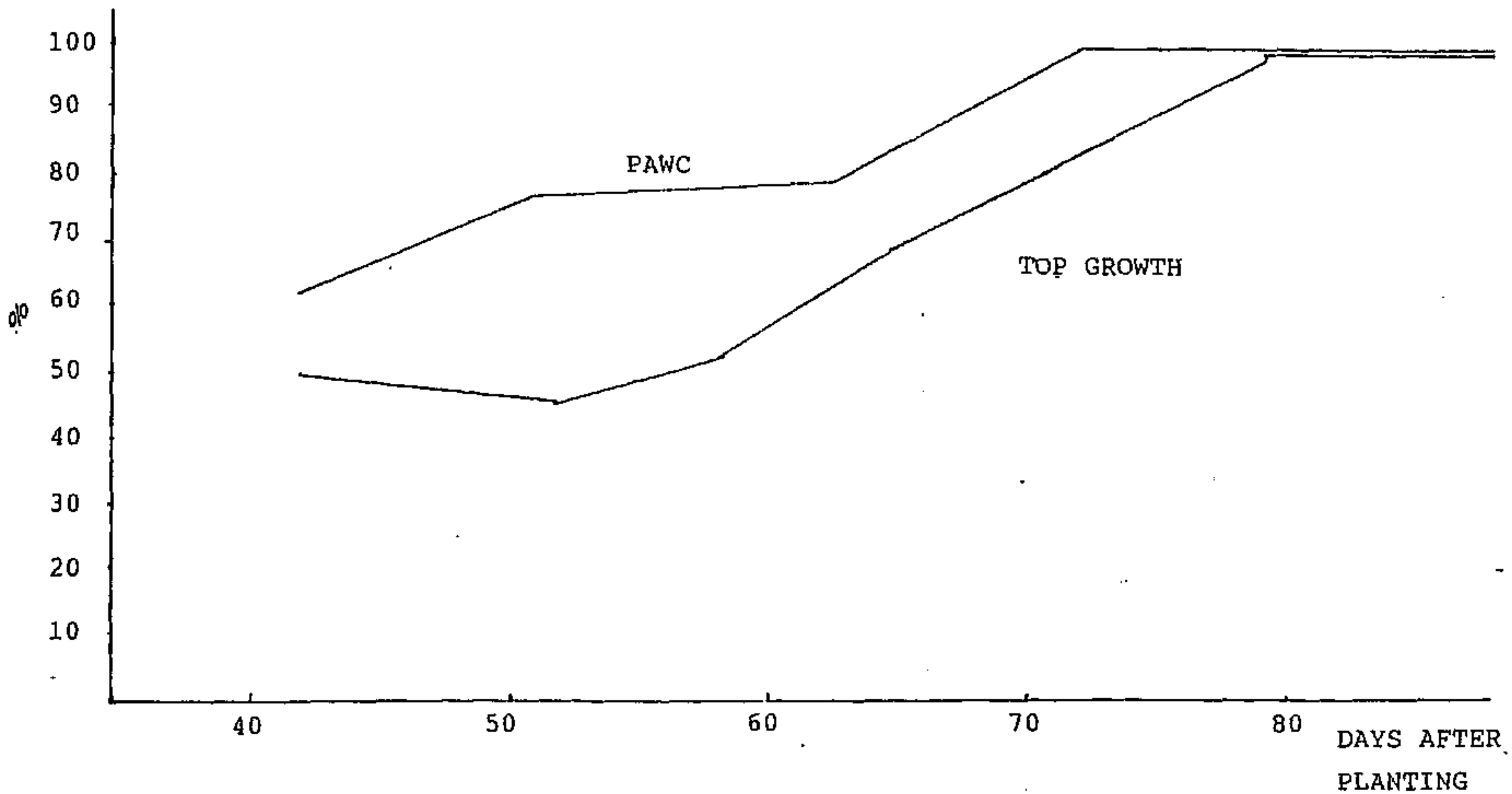


FIG.3.27 RELATIVE PAWC AND RELATIVE TOP GROWTH OF WHEAT AT SITE D16 (1986 SEASON)

(1982) and Boedt & Laker (1985) found on soils with root-restricting subsoils.

TABLE 3.9 - Quantities of soil water extracted by wheat at different soil depths and PAWC values for each growth stage at site D16 (1986 season)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	d
0- 100	7,3	8,5	7,3	8,2
100- 200	7,0	9,3	7,3	8,2
200- 300	6,8	10,8	8,7	11,0
300- 400	9,8	13,0	11,5	14,5
400- 500	9,5	12,5	12,3	16,0
500- 600	7,0	9	10,8	15,3
600- 700	7,8	8,0	9,3	13,0
700- 800	8,0	7,5	7,8	10,5
800- 900	7,5	7,3	6,7	8,2
900-1000	6,5	7,8	8,0	9,0
1000-1100	5,8	7,0	7,8	8,2
1100-1200	5,5	6,0	5,7	7,5
1200-1300	1,8	2,0	4,8	6,0
1300-1400			3,0	4,5
1400-1500			1,3	3,0
1500-1600				
PAWC	90,3	109,0	112,3	143,1

3.2.1.2.3 Effects of soil water stress at different growth stages

The effects of soil water stress on vegetative growth were very clear at the end of the experiments. The plants on the stressed plots were shorter than those on the well-watered control plots at all sites (Table 3.10). The smallest differences were measured at site D6. This is in line with the results of the 1985 winter experiments and is attributed to the high amount of available water in the upper part of the profile. The compacted B horizon causes a very slow drainage and more water stays available for a longer time.

TABLE 3.10 - Length of the wheat plants at the end of the experiments at sites D6, D12 and D16 (1986 season)

Plot	Total length (mm)			
	D6	D12	D16	average
a	640	630	620	630
b	590	480	470	510
c	540	520	530	530
d	610	590	600	600
e	660	660	620	650
			lsd (p=0,05)	52
			(p=0,01)	75

The data listed in Table 3.10 were statistically analyzed. The design of the experiments is a randomized complete block design with the inducing of water stress at different growth stages (plots a, b, c, d and e) as experimental units and sites D6, D12 and D16 as blocks. The variation (i.e. differences in soil profile characteristics) among units within a block is less than that among units in different blocks. The analysis of variance for any number of treatments for a randomized complete block design as described by Steel & Torrie (1980) was used. The analysis showed that there were significant differences between the treatment means (Table 3.11).

TABLE 3.11 - Differences between final length means of wheat stressed at different growth stages (1986 season)

Growth stages	b	c	d	a
e	140**	120**	50	20
a	120**	100**	30	
d	90**	70*		
c	20			

** significant at 1% level
* significant at 5% level

Soil water stress induced during growth stages b and c, i.e. shortly before and during appearance of the flag leaf (stages 7 to 9 according to Large, 1954) resulted in significantly shorter plants relative to those which were stressed before and after this period (stages a and d) and to those of the control plot. This illustrates that wheat is sensitive to soil water stress, as far as vegetative growth is concerned, during a period starting with the appearance of the second node (stage 7 according to Large, 1954) and ending with the completion of flag leaf development (stage 9 according to Large, 1954). When soil water stress was induced before this period the plants still recuperated and reached a final length more or less equal to that of non-stressed plants. Soil water stress after this period had no effect on the final length of the plants as the vegetative growth stage had ended by that time.

Although the yields of the stressed treatments were lower than that of the control treatment, statistical analysis (analysis of variance for any number of treatments for a randomized complete block design) of the data listed in Table 3.12 indicated that there were no significant differences between the different treatments. However, a least significant difference of 1,00 ton/ha (unprotected by F-test, p=0,05) indicated that the yield of treatment c (stressed at appearance of flag leaf) was significantly lower than that of the control plot. The lower yields at site D16 relative to sites D6 and D12 are probably the result of damage by birds. Site D16 was somewhat distant from sites D6 and D12 and could not be watched as intensively as the latter.

TABLE 3.12 - Grain yields of wheat at sites D6, D12 and D16 (1986 season)

Plot	Grain yields (ton/ha)			
	D6	D12	D16	average
a	4,00	4,09	3,10	3,73
b	4,21	4,01	2,98	3,73
c	3,26	2,62	3,86	3,25
d	3,58	4,20	3,67	3,82
e	4,13	4,57	4,16	4,29
average	3,84	3,90	3,55	

3.2.2 Durum wheat

The growth stages at which drying cycles for durum wheat were started are listed in Table 3.13.

TABLE 3.13 - Growth stages at which drying cycles for durum wheat were started during the 1987 winter season at sites D6, D12 and D16

Plot no.	Phenological stage	Days after planting
a	tillering	45
b	leaf sheaths erected	65
c	flag leaf appears	80
f	ears appear	100

3.2.2.1 Stem elongation and pre-dawn leaf water potential patterns

During the experiments it was found that PLWP of young, immature leaves were constantly lower than those of mature leaves. In some cases they had very low values, apparently indicating FMS, while no signs of stress could be detected in the mature leaves. This confirms the statement of Boedt & Laker (1985) that it is very important to standardize on the plant part used for PLWP determinations. For durum wheat it is clearly very important to use mature leaves and the readings, therefore, were always done on the youngest mature leaf. The results of the determinations done on immature leaves are also indicated on the PLWP graphs (discussed later in this paragraph) in order to indicate the discrepancies between immature and mature leaves. Similar tests done on wheat at site ISO showed no difference between the values for immature leaves and those of mature leaves. When FMS was observed, the drying cycles were prolonged and PLWP readings were continued for some time after the onset of stress.

The stem elongation patterns of plots D6a and D6e (the well-watered control plot) were similar until 35 days after the start of the drying cycle i.e. 80 days after planting. However, the stem elongation rate on plot D6a decreased markedly already on day 24 of the drying cycle (Figure 3.28). From day 24 until day 35 of the drying cycle the cumulative stem elongation on plot D6a decreased slightly relative to that of the control plot. After day 35, the gap between the two cumulative stem elongation lines started to widen very quickly, indicating severe water stress. During the first 19 days of the drying cycle PLWP values were quite stable around -200kPa. The next ten days PLWP readings fluctuated around an average of about -500kPa and a minimum value of -750kPa was measured on day 24 of the drying cycle, indicating FMS. As the result of a decrease in air temperature from 27 °C to 10,5 °C on days 24 to 28 of the

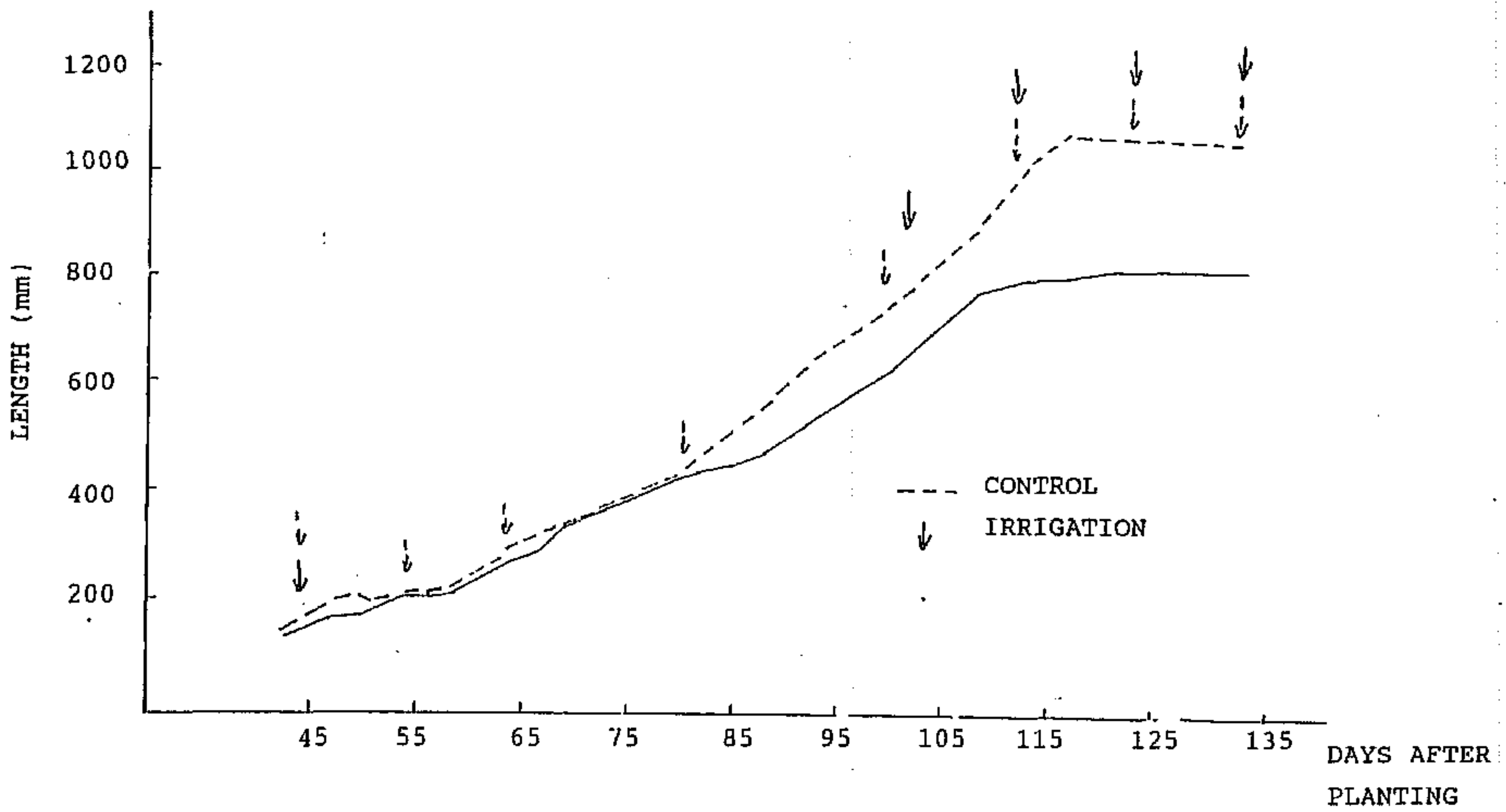


FIG.3.28 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D6a (1987 SEASON)

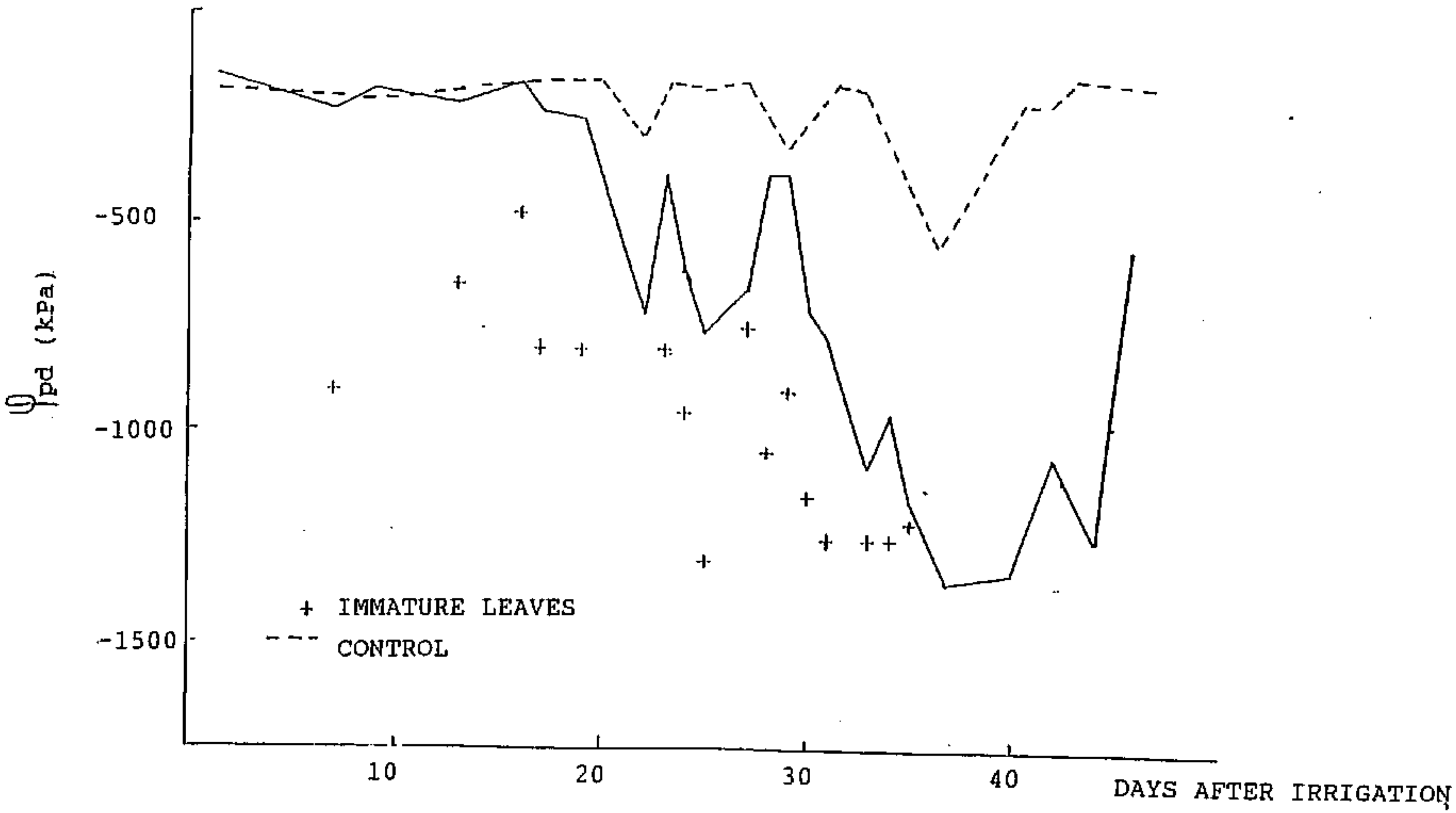


FIG.3.29 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D6a (1987 SEASON)

drying cycle, PLWP values increased again to about -400kPa. After the 29th day of the drying cycle PLWP dropped very sharply and stayed below -1000kPa with slightly fluctuating values (Figure 3.29). Normally, only PLWP values below a certain value (-1000kPa) are considered to be an indication of FMS. This is analogous with the "Crop water stress index" (CWSI) concept of Idso, Jackson, Pinter, Reginato & Hatfield (1981) which uses canopy temperatures (measured with infra-red thermometer) combined with vapour pressure deficit determinations to calculate the crop water stress index (Jackson, Idso, Reginato & Pinter, 1981). The CWSI starts differing from that of a well-watered crop as the crop depletes the soil profile but harmful stress is only indicated when the CWSI reaches a certain value (1). However, the results obtained with wheat also showed that during young growth stages relatively higher PLWP are to be considered as an indication of FMS. Large differences between values of mature and immature were found, with those of immature leaves constantly lower than those of mature leaves.

On plot D12a the stem elongation rate also decreased 24 days after the start of the drying cycle (Appendix 3.1.20). This coincided with the day on which a minimum PLWP value of -900kPa was measured, indicating FMS

(Appendix 3.2.12). As in the case of D6a, PLWP increased again from day 25 until day 28 of the drying cycle.

From the start of the drying cycle, the plants on plot D16a were taller than those on plot D16e and their stem elongation lines ran parallel until 24 days after the start of the drying cycle on plot D16a. Then the growth of the plants on plot D16a started slowing down relative to the control, indicating FMS (Appendix 3.1.21). PLWP started differing from that of the control plot on day 19 and fluctuated with decreasing minima. On day 24 a minimum value of -900kPa was measured. Thereafter, the pattern was somewhat different from those found on plots D6a and D12a, as a more explicit fluctuating phase was found (Appendix 3.2.13). As in the case of plots D6a and D12a, light rainfall on day 44 of the drying cycle caused a temporary increase in PLWP. Again it was found that the PLWP values for immature leaves were constantly lower than those of mature leaves. On some days they even indicated FMS on the well-watered control plots.

At the end of the growing season, the plants on plots D6a, D12a and D16a were markedly shorter (200mm to 250mm) than those on the respective control plots (Figure 3.28 and Appendices 3.1.20 and 3.1.21).

The drying cycles on the b plots were started 65 days after planting. At that stage the plants had an average height of 300mm on all plots (end of tillering stage, leaf sheaths erected). The stem elongation on plot D6b was similar to that observed on control plot D6e until day 21 of the drying cycle. At that time the growth rate of the plants on plot D6b started to decrease relative to that of the control, indicating FMS. The gap between the stem elongation lines of D6b and D6e gradually widened. The growth rate on D6b did not recover after rewatering (Figure 3.30). The drop in PLWP was observed 25 days after the final irrigation, i.e. four days after the stem elongation started decreasing. The values dropped overnight from -300kPa to -1300kPa, whereas the values for the control plot remained above -500kPa (Figure 3.31).

FMS on plot D12b was observed on day 26 of the drying cycle when PLWP values dropped overnight from -250kPa to -1300kPa, followed by a decrease in stem elongation on day 27 (Appendices 3.1.22 and 3.2.14). Low PLWP values (-1000kPa) were measured 18 days after the start of the drying cycle on plot D12b. A drop of PLWP (to -600kPA) was also observed on control plot D12e on that day and was caused by a sudden increase in temperature (from 21 °C to 32 °C). Similar decreases in PLWP at that time were

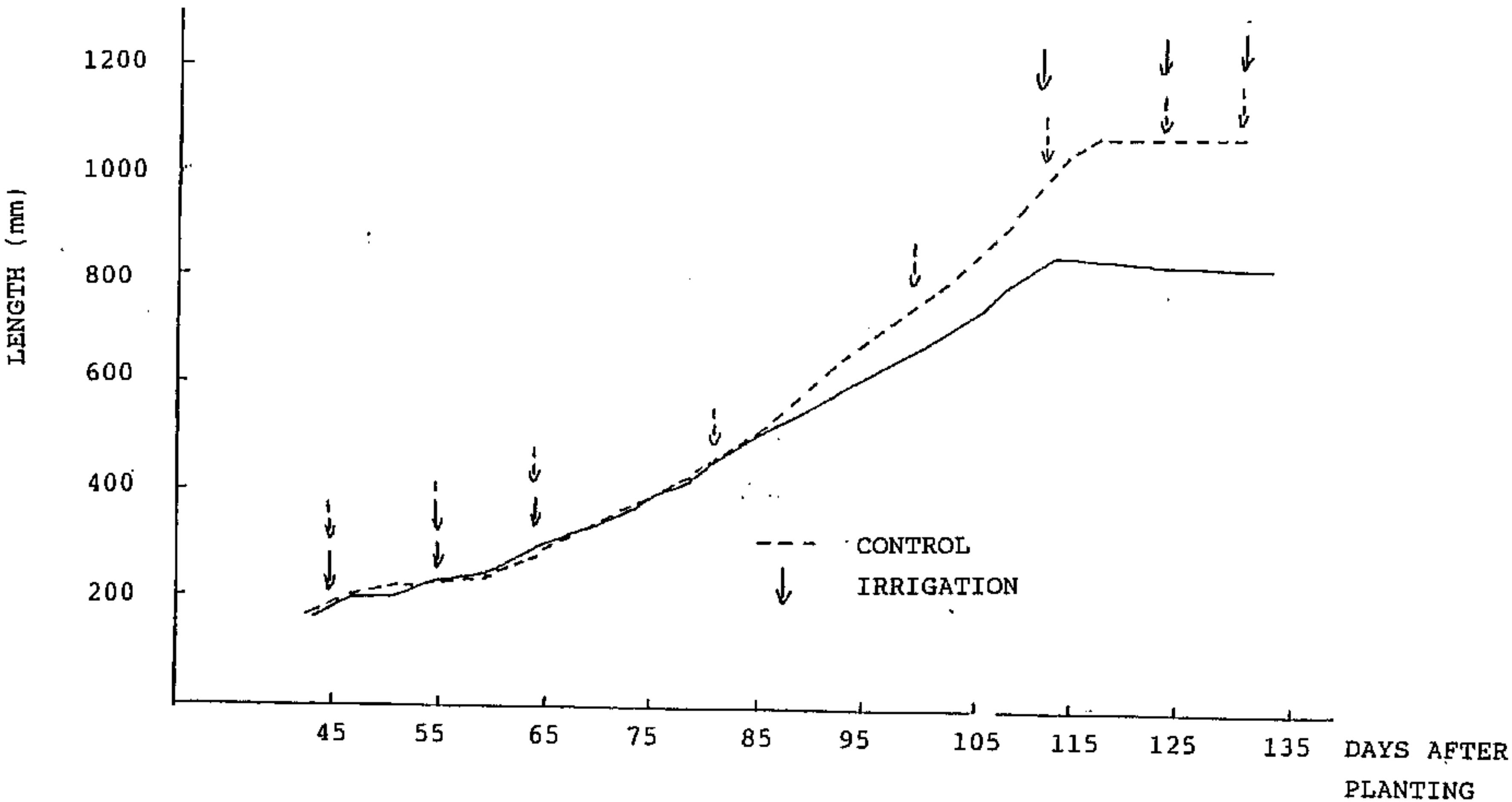


FIG.3.30 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D6b (1987 SEASON)

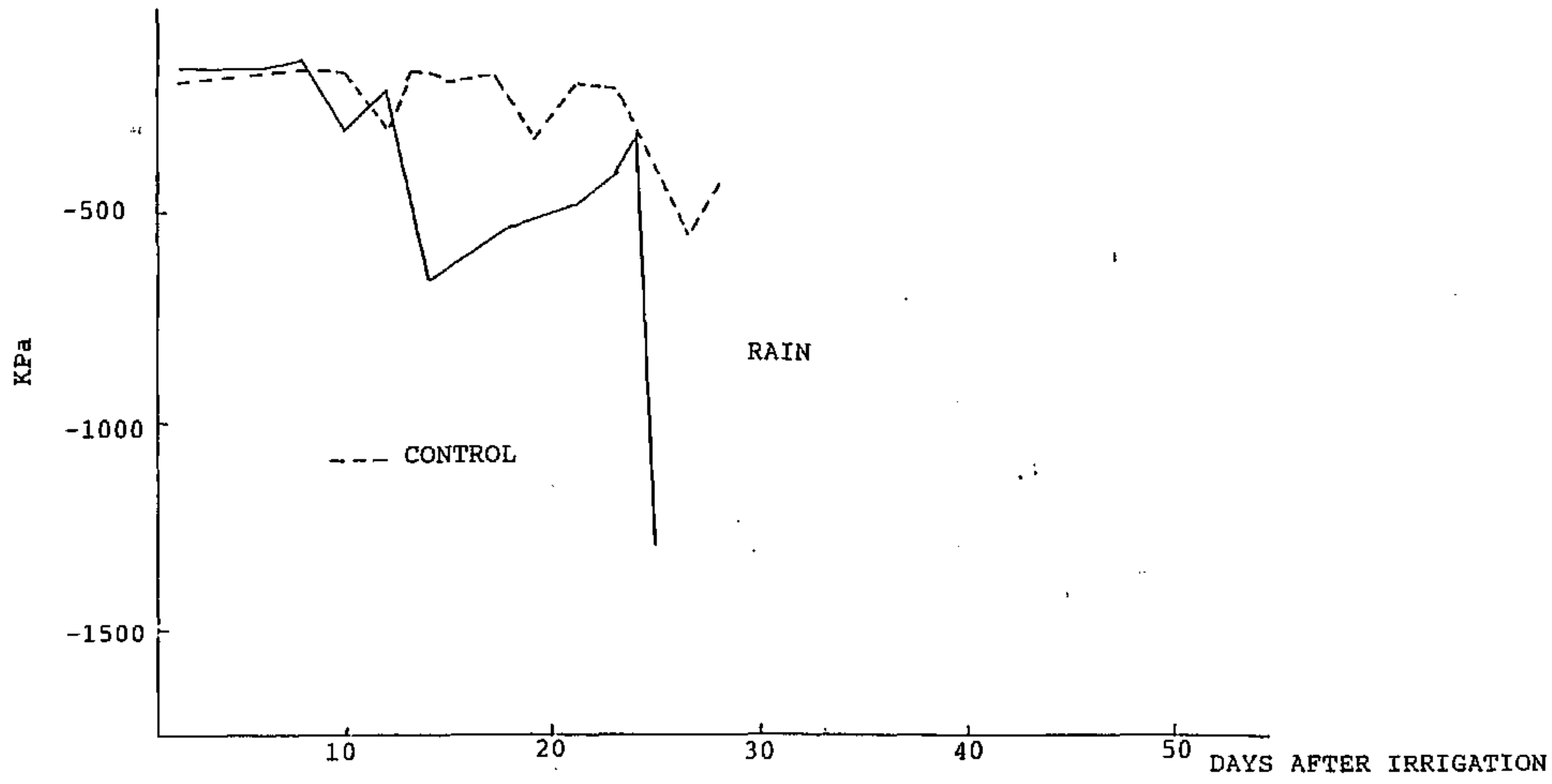


FIG:3.31 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D6b (1987 SEASON) also observed at sites D6 and D16.

The results found on plot D16b were similar to those found on D12b. PLWP indicated FMS on day 24 of the drying cycle when values dropped overnight to -1400kPa. The decrease in stem elongation was measured three days later, i.e. on day 92 after planting (Appendices 3.1.23 and 3.2.15). As in the case of plots D6b and D12b, no fluctuating phase was found in the PLWP pattern of plot D16b.

At the end of the growing season the plants on plots D6b, D12b and D16b were 250mm to 300mm shorter than the plants on the respective control plots.

The drying cycle on the c plots was started 80 days after planting (appearance of flag leaf). The stem elongation pattern of the plants on plot D6c could not clearly indicate FMS. As the plants were nearly fully grown (appearance of ears), soil water stress had little effect on the vegetative growth and a difference in height of only 40mm between the plants of plot D6c and control plot D6e was measured (Figure 3.32). The PLWP pattern indicated FMS on day 29 of the drying cycle (Figure 3.33). The values dropped very sharply from -350kPa to -1250kPa and stayed below -1000kPa until the plot was

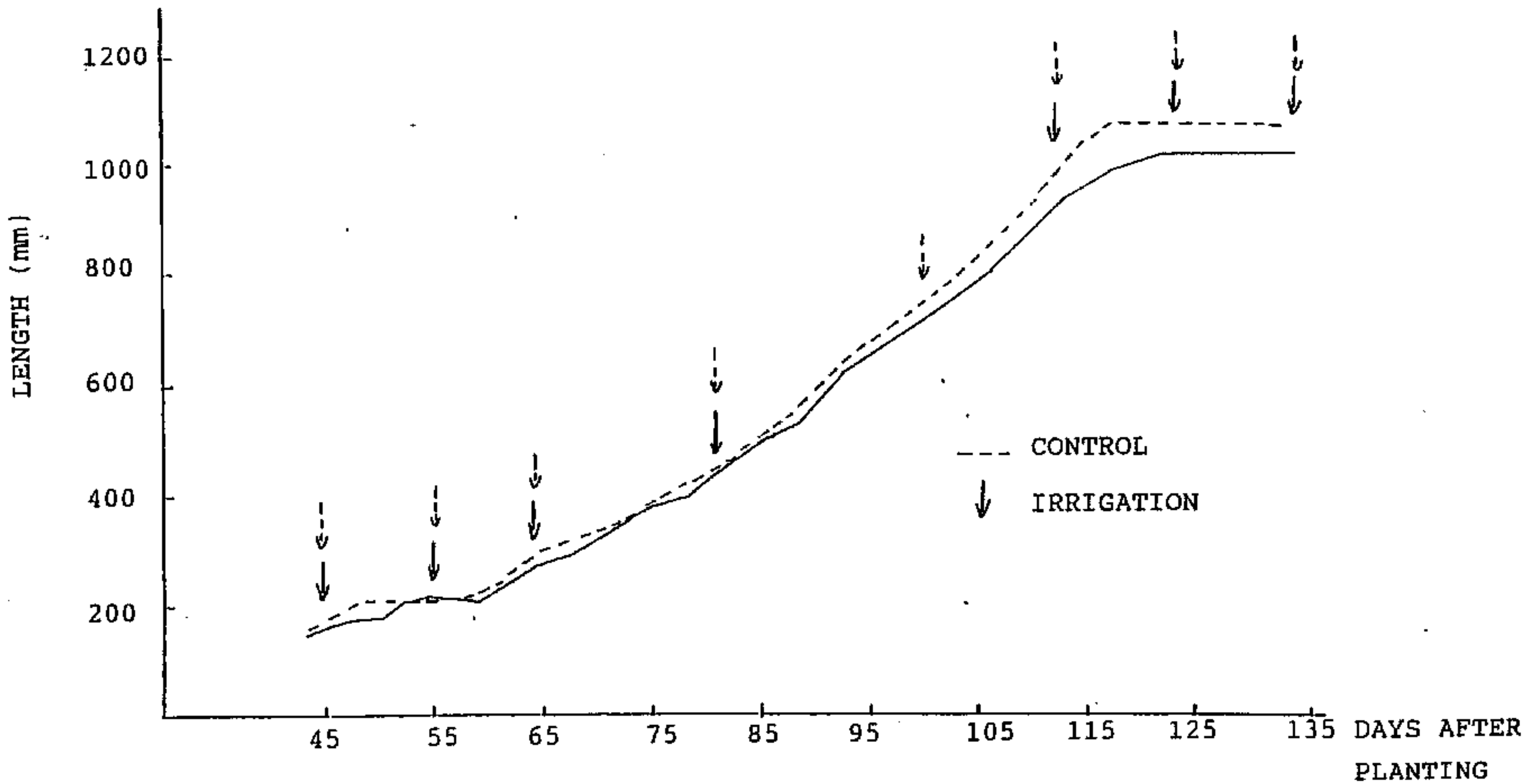


FIG.3.32 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D6c (1987 SEASON)

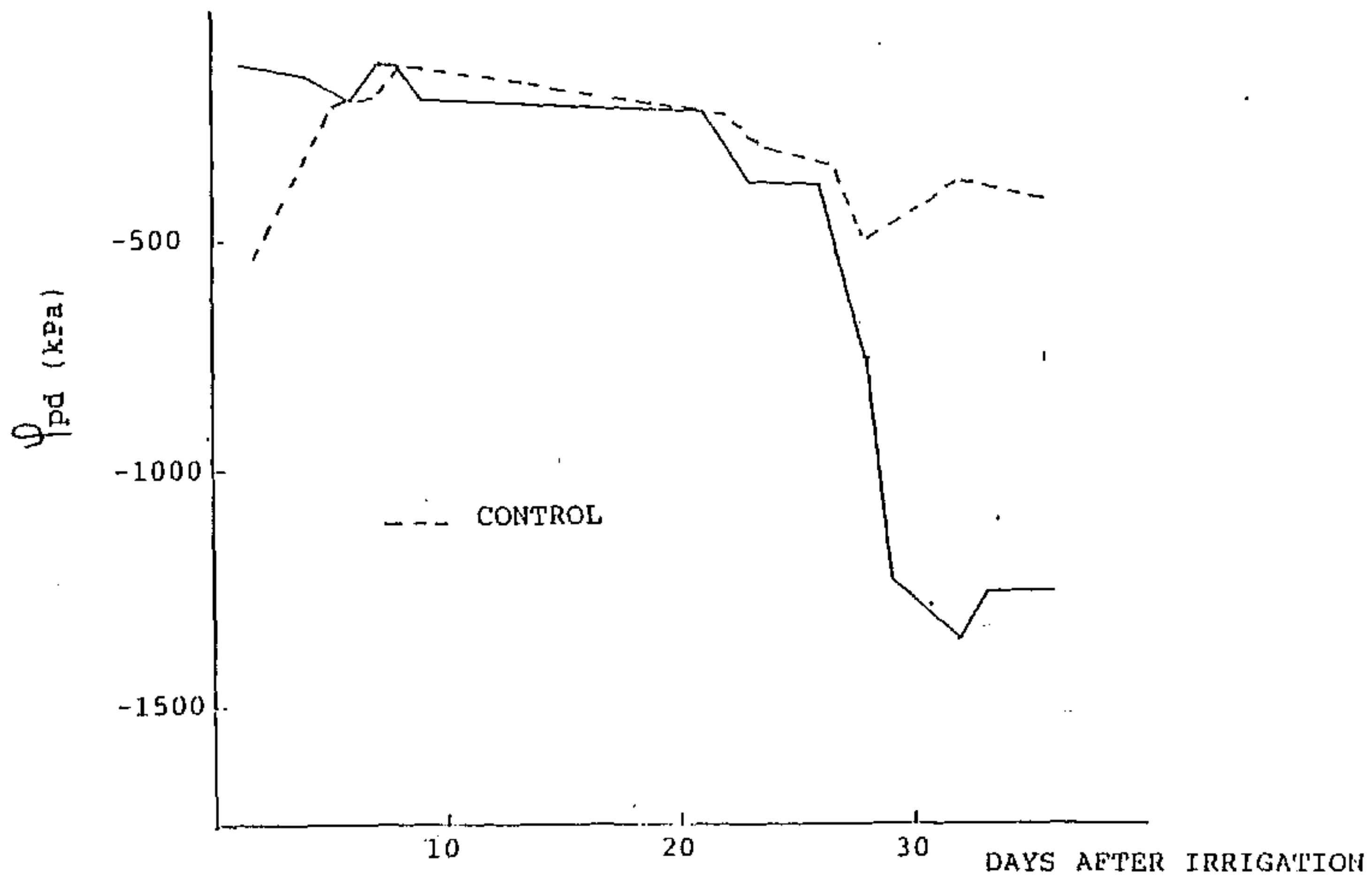


FIG.3.33 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D6c. (1987 SEASON)

irrigated again. This was also observed on the other plots.

The results obtained on plot D12c were somewhat different from those of plot D6c: the PLWP pattern indicated FMS on day 29 of the drying cycle, one day after the stem elongation started to decrease relative to that of the control plot (Appendices 3.1.24 and 3.2.16). PLWP dropped sharply to -1200kPa, whereas the PLWP for the control plot remained at -200kPa. As in the case of plot D6c, the difference in total height at the end of the season was only 40mm.

The results obtained on plot D16c were identical to those for plot D12c. The drop in PLWP and stem elongation rate occurred on the same days (day 29 and 28 of the drying cycle respectively) as on plot D12c (Appendices 3.1.25 and 3.2.17). As in the case of plots D6c and D12c, a difference of only 40mm in total height of the plants on plots D16c and the control plot was measured at the end of the experiments.

The drying cycle on the f (flowering) plots was started 100 days after planting, when the ears were appearing. The stem elongation patterns could not indicate FMS because the vegetative growth stage had ended at the time that water stress was induced (grain filling stage). At the end of the experiments no difference in height between the plants on the f and e (control) plots was measured (Figure 3.34 and Appendices 3.1.26 and 3.1.27). At all three sites PLWP for the f plots decreased gradually until day 19, after which a clear drop to far below -1000kPa occurred. PLWP patterns, therefore, indicated FMS on day 20 of the drying cycle at all sites (Figure 3.35 and Appendices 3.2.18 and 3.2.19). The period to reach FMS on the f plots was shorter relative to the other plots because of the peak demands during the drying cycle as a result of the advanced growth stage and also because of the high evaporative demand as a result of the relatively high temperatures during the drying cycle (28 °C to 32 °C during the second half of the drying cycle).

The number of days to reach FMS and the parameter which indicated FMS of durum wheat for the different growth stages at sites D6, D12 and D16 are summarized in Table 3.14.

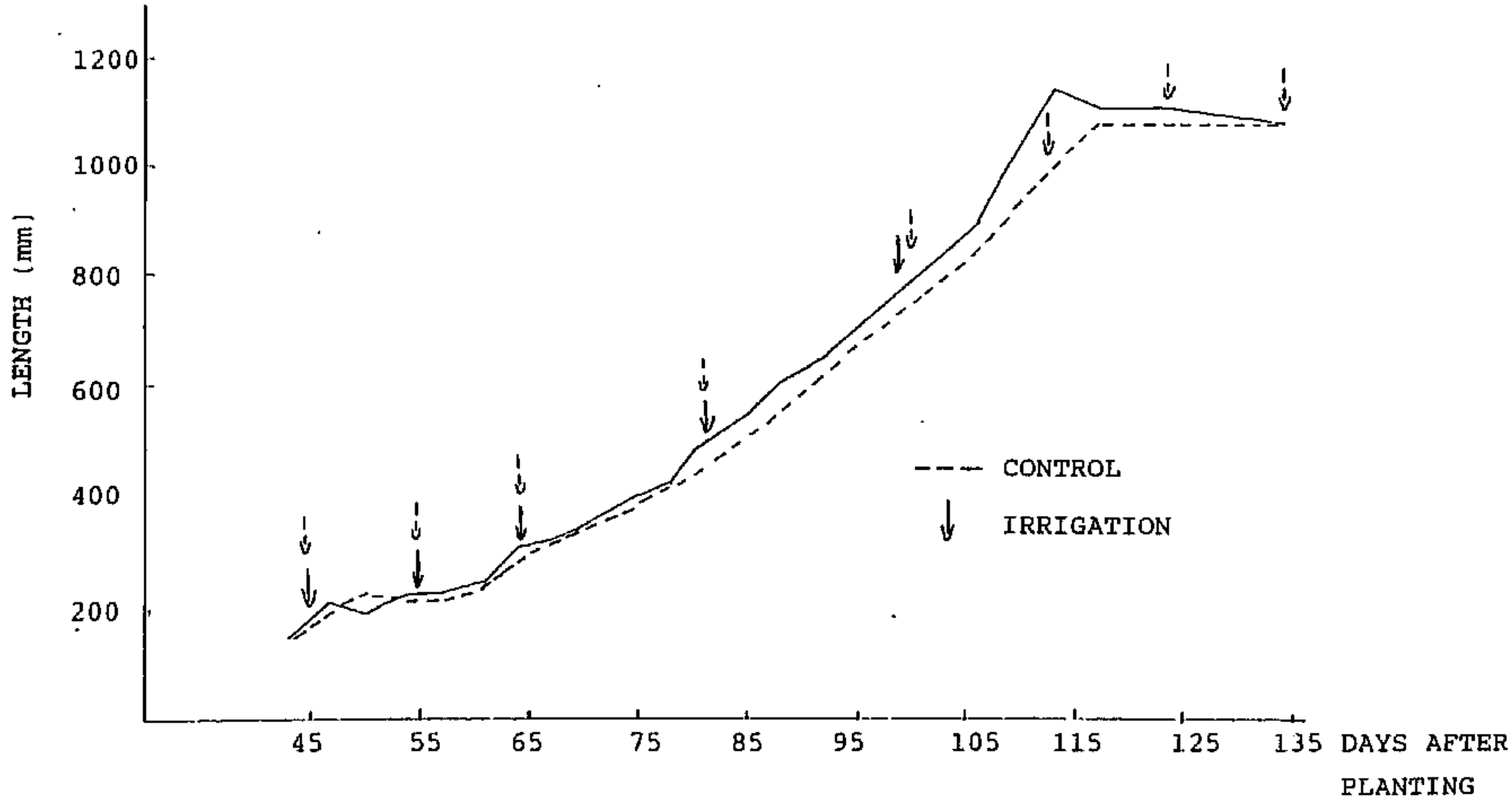


FIG.3.34 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D6 f (1987 SEASON)

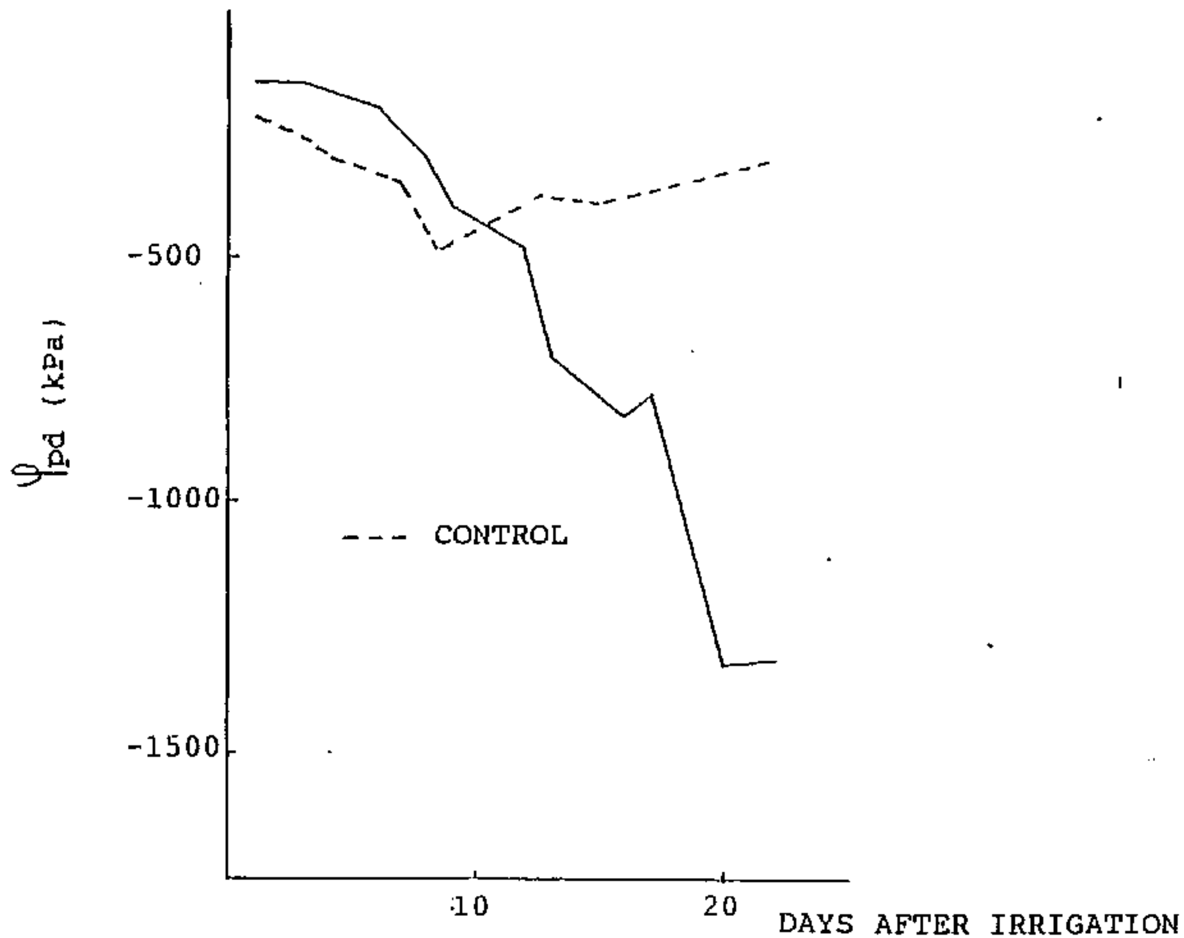


FIG.3.35 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D6f (1987 SEASON)

TABLE 3.14 - Number of days to reach FMS and parameter which indicated FMS of durum wheat at different growth stages at sites D6, D12 and D16 (1987 season)

Plot no	Days to FMS	Parameter *
D6a	24	PLWP and SER
D6b	25	PLWP and SER
D6c	29	PLWP
D6f	20	PLWP
D12a	24	PLWP and SER
D12b	26	PLWP and SER
D12c	29	PLWP and SER
D12f	20	PLWP
D16a	24	PLWP and SER
D16b	24	PLWP and SER
D16c	29	PLWP and SER
D16f	20	PLWP

* PLWP: Pre-dawn leaf water potential.
SER : Stem elongation rate.

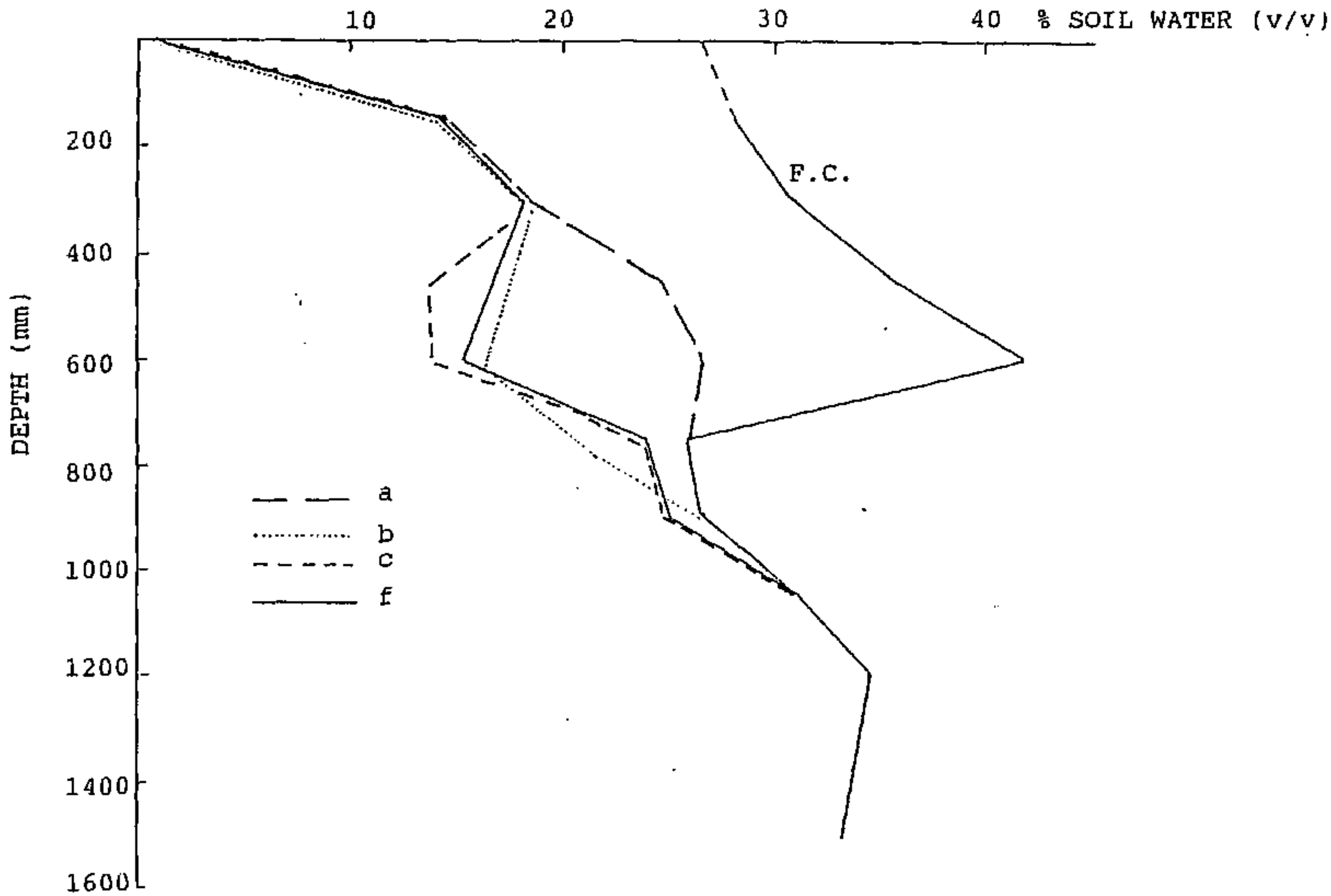
TABLE 3.15 - Quantities of soil water extracted by durum wheat at different soil depths and PAWC values for each growth stage at site D6 (1987 season)

Depth (mm)	Soil water extracted (mm)				
	a	b	c	f	flow. 1985
0- 100	17,0	18,0	16,8	18,0	15,0
100- 200	12,5	13,0	11,7	13,5	13,0
200- 300	12,0	12,0	11,5	12,8	11,8
300- 400	11,8	16,8	18,5	17,0	13,5
400- 500	12,5	21,0	24,0	22,0	17,8
500- 600	14,7	25,5	28,0	28,0	23,8
600- 700	5,0	11,5	10,0	9,7	9,0
700- 800		3,5	1,5	1,8	
800- 900			1,0	1,5	
900-1000				0,5	
1000-1100					
PAWC	85,5	121,3	123,0	124,8	103,9

3.2.2.2 PAWC values and soil water extraction patterns

The soil water extraction patterns for site D6 are illustrated in Figure 3.36. The basic shape of the patterns was identical to the shape found for wheat, but the PAWC values for durum wheat were lower than those for wheat. As the plants grew older, more soil water was extracted from soil layers between 400mm and 600mm depth and not from layers deeper in the profile as the compacted B horizon impeded root growth and penetration. Table 3.15 shows the quantities of soil water extracted at different soil depths and the PAWC values for the four growth stages. The extraction of soil water from soil layers between 400mm and 700mm depth at stage d was twice the amount measured at stage a in this part of the profile. In a small experiment during the 1985 winter season a PAWC value of 104mm was found for durum wheat at flowering stage (Table 3.15). The PAWC value found at stage f during this season was about 17% higher than the value found at flowering stage during the 1985 season. The higher value is supported by the values found at growth stages a, b and c. Two possible reasons for this difference can be named: Firstly, the change of cultivar from Fargo in 1985 to Moni during this season. Secondly, the incomplete wetting of the soil profile before planting during the 1985 season which caused weak root

FIG.3.36 SOIL WATER EXTRACTION PATTERNS OF DURUM WHEAT AT FIRST MATERIAL STRESS AT DIFFERENT GROWTH STAGES AT SITE D6 (1987 SEASON)



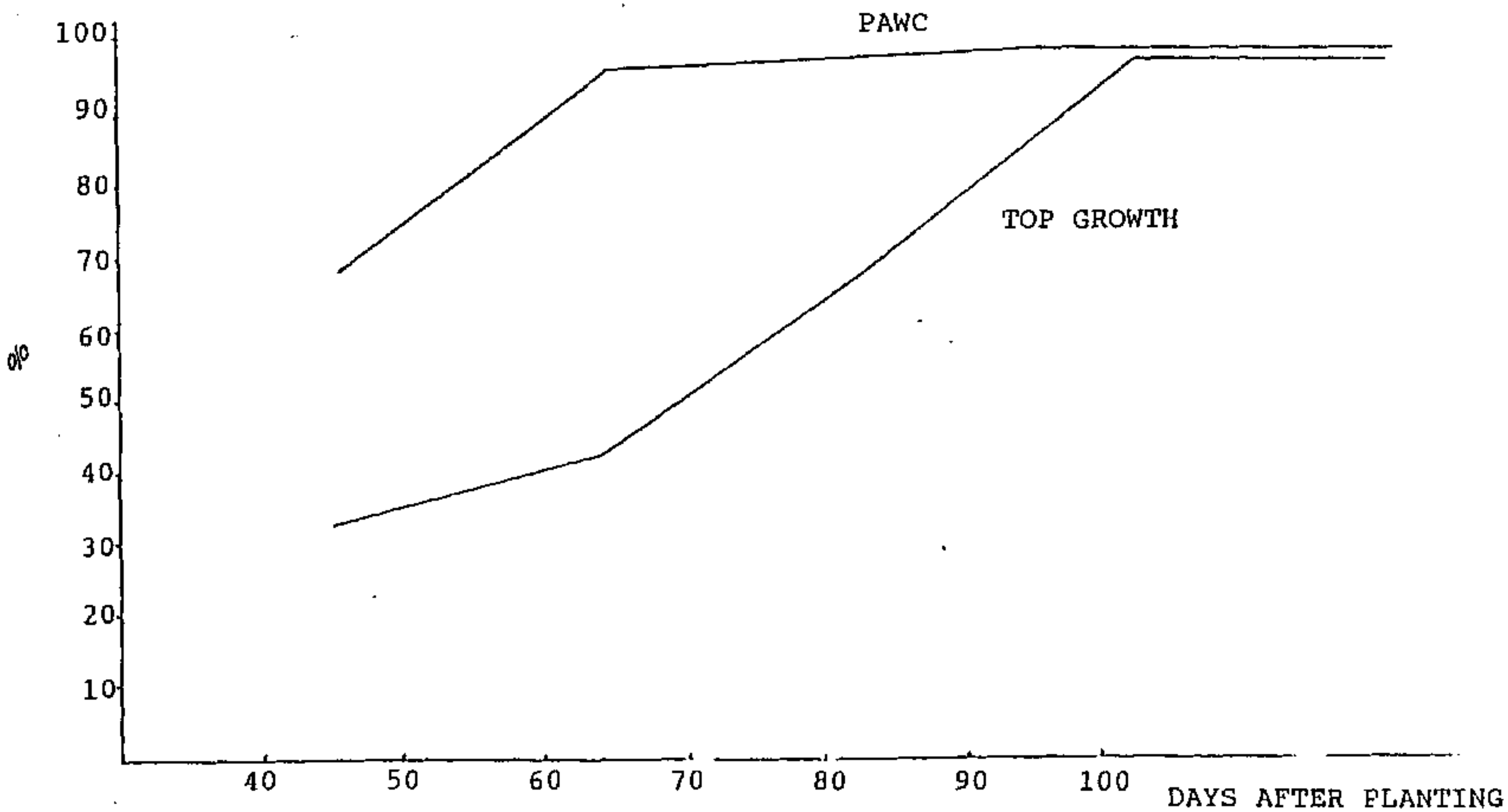


FIG.3.37 RELATIVE PAWC AND RELATIVE TOP GROWTH OF DURUM WHEAT AT SITE D6 (1987 SEASON).

development. The smaller extraction below a depth of 400mm. measured during the 1985 season supports the second theory. The PAWC determined at flowering (stage f) was already reached at stage b where the drying cycle was started 65 days after planting, at the end of tillering stage, and FMS occurred on day 90 after planting (Figure 3.37)

The soil water extraction patterns for site D12 are presented in Appendix 3.3.5. Their basic pattern was identical to the pattern found for wheat, but the PAWC values for durum wheat were lower. It was a fan shaped pattern and the convergence point, marking the lower boundary of the effective root zone, moved deeper as the plants grew older. On plot D12a the convergence point was found at a depth of 750mm and already on plot D12b the maximum depth of 1000mm was reached. The quantities of soil water extracted at different soil depths and the PAWC values for each growth stage are listed in Table 3.16. Again a much higher PAWC value was obtained during this season compared to the 1985 experiment (see also D6). The increase of the PAWC from stage a to stage f (flowering) is caused by a higher extraction from soil layers deeper in the profile while the extraction in the upper part of the profile remained more or less constant. The maximum PAWC value (stage f) was already reached at

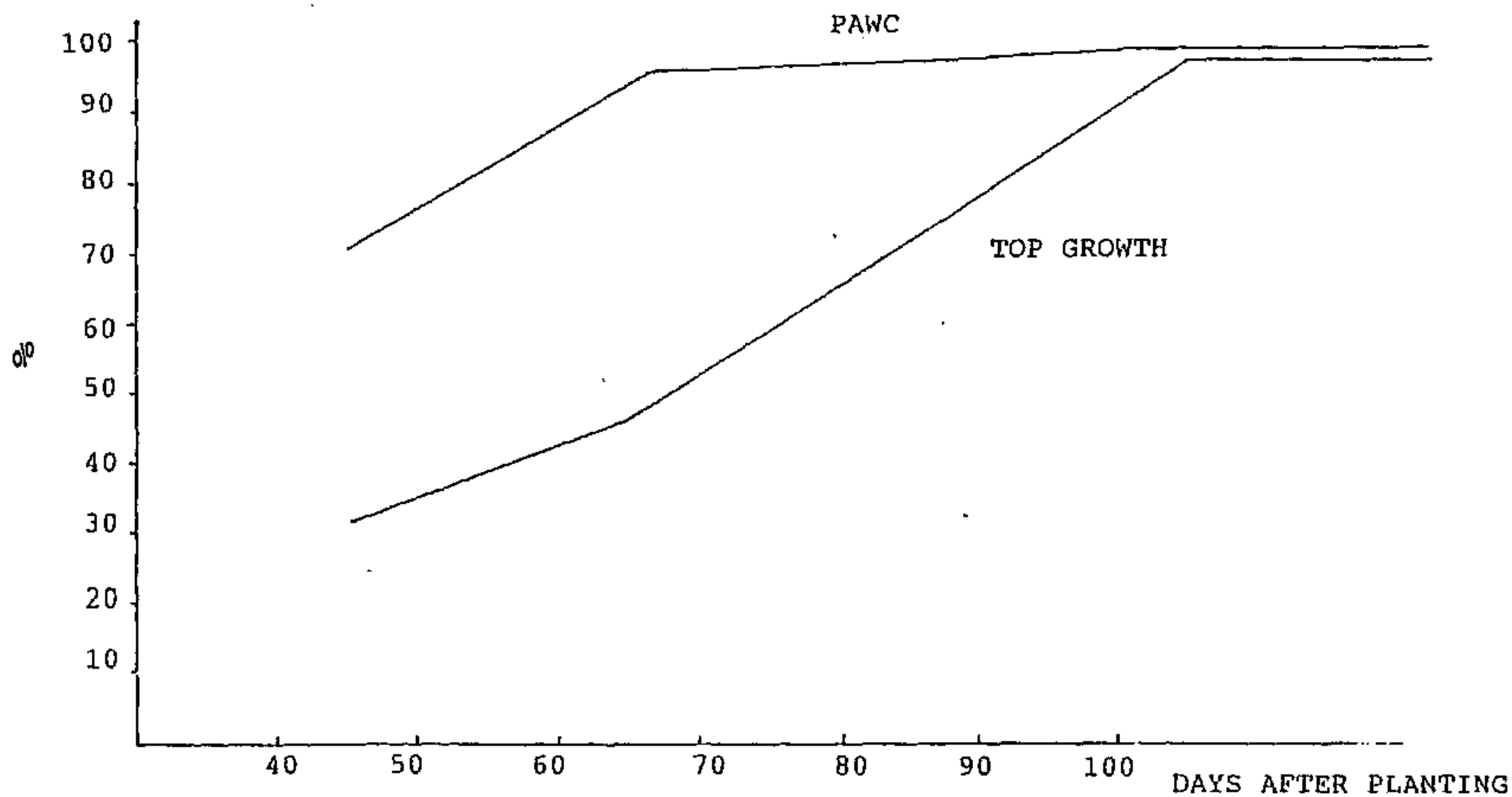


FIG.3.38 RELATIVE PAWC AND RELATIVE TOP GROWTH OF DURUM WHEAT AT SITE D12 (1987 SEASON)

stage b where the drying cycle was started at the end of tillering stage, i.e. 65 days after planting (Figure 3.38). These results were similar to those found at site D6 and they confirmed that the PAWC at flowering stage is already reached long before this stage.

TABLE 3.16 - Quantities of soil water extracted by durum wheat at different soil depths and PAWC values for each growth stage at site D12 (1987 season)

Depth (mm)	Soil water extracted (mm)				
	a	b	c	f	flow. 1985
0- 100	17,0	18,0	18,0	18,0	13.0
100- 200	13.5	13,8	13,8	14,8	12,5
200- 300	14,8	13,3	12,7	14,7	13,3
300- 400	13.2	12,5	12,3	13,0	12,5
400- 500	11,0	11,5	12,3	12,8	11,0
500- 600	8.0	11,0	12,8	13,7	9,5
600- 700	2,8	9,0	9,0	9,8	8.0
700- 800		7.5	7,2	7,2	7,5
800- 900		6,8	7,2	6,0	
900-1000		2,0	2,5	1.8	
1000-1100					
1100-1200					
PAWC	80,3	105,4	107,8	111,8	87,3

The soil water extraction patterns found at site D16 had a different shape compared to those of sites D6 and D12 (Appendix 3.3.6). A more or less constant extraction of water per unit of depth resulted in parallel running first stress and field capacity lines. This is similar to the pattern found for wheat on this site and the patterns found with wheat on the deep sandy soils at Vaalharts by

Boedt & Laker (1985). Again PAWC values for durum wheat were lower than those for wheat. An increase in soil water extraction from soil layers between 300mm and 500mm depth, however, resulted in a bulging first stress line in this part of the profile. The maximum depth of soil water extraction was already reached at stage a (FMS before appearance of the flag leaf) and the evolution of the extraction patterns, going from stage a to stage f, consisted in a widening of the gap between the first stress and field capacity lines. The quantities of soil water extracted at different depths and the PAWC values for each growth stage are listed in Table 3.17. The increase of the PAWC as the plants grew older was due to an increase of soil water extraction throughout the profile. The PAWC at flowering stage was already reached at stage b and this confirmed the results obtained at sites D6 and D12 (Figure 3.39). The maximum PAWC value (stage f) was much higher than the value found at flowering stage during the 1985 season. This was also found at sites D6 and D12 and was explained by the fact that the soil profile was not filled to field capacity before planting during the 1985 season. A dry subsoil impeded root development and root penetration resulting in a poorly developed root system and a lower PAWC during 1985. Proof for this can be found in Table 3.17. The soil water extraction below 500mm during the 1985 season was

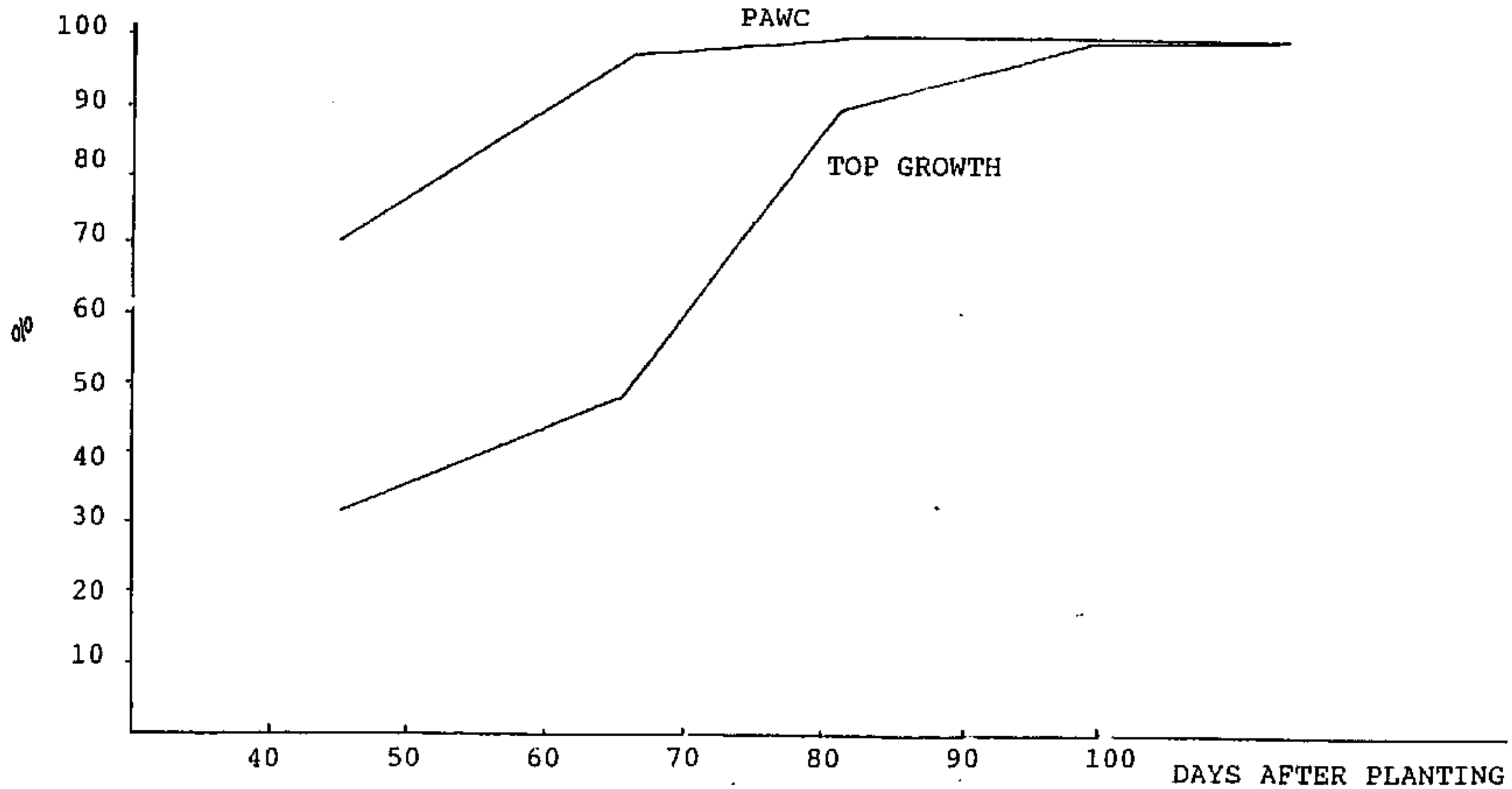


FIG.3.39 RELATIVE PAWC AND RELATIVE TOP GROWTH OF DURUM WHEAT AT SITE D16 (1987 SEASON)

much smaller than during this season.

TABLE 3.17 - Quantities of soil water extracted by durum wheat at different soil depths and PAWC values for each growth stage at site D16 (1987 season)

Depth (mm)	Soil water extracted (mm)				
	a	b	c	d	flow. 1985
0- 100	13,8	13,0	11,0	12,3	9,7
100- 200	8,7	9,5	7,5	8,5	11,5
200- 300	9,5	13,8	12,8	12,7	9,8
300- 400	11,0	16,5	15,5	16,0	7,7
400- 500	10,5	14,7	14,3	15,7	6,0
500- 600	8,0	10,5	12,0	12,5	6,7
600- 700	7,8	10,0	10,3	10,5	6,7
700- 800	6,0	9,0	9,0	8,7	5,0
800- 900	3,3	7,2	8,8	8,0	3,8
900-1000	4,2	7,7	8,5	7,5	2,7
1000-1100	4,5	7,5	8,5	7,5	1,8
1100-1200	4,0	6,0	8,0	7,2	
1200-1300	1,2	2,0	2,8	2,5	
1300-1400					
PAWC	92,5	127,2	129,0	129,6	81,4

TABLE 3.18 - PAWC values of wheat and durum wheat at flowering stage and ratio of PAWC of durum wheat to PAWC of wheat for sites D6, D12 and D16 (numbers between brackets indicate year of determination)

Site	PAWC (mm)		ratio (%)
	durum wheat	wheat	
D6	125 (1987)	145 (1986)	86
D12	112 (1987)	132 (1986)	85
D16	130 (1987)	143 (1986)	91

The PAWC values for wheat and durum wheat and the ratio of the PAWC of durum wheat to that of wheat are listed in Table 3.18. For both sites D6 and D12 the ratio was 85%, while for site D16 a ratio of 91% was found. This would give an average ratio of more or less 87%.

3.2.2.3 Effects of soil water stress on vegetative growth and yield

The effects of soil water stress on vegetative growth are illustrated in Table 3.19 which shows the height of the plants on the different plots at the end of the experiments. The effects were the smallest at site D16 and the reason for this was the very effective and deep root system. The smallest plants were found on the plots where water stress was induced during the appearance of the flag leaf (b-plots). The data in Table 3.19 were statistically analyzed using the method for any number of treatments for a randomized complete block design described by Steel & Torrie (1980).

TABLE 3.19 - Height of durum wheat at the end of the vegetative growth period (flowering stage) at sites D6, D12 and D16 (1987 season)

Plot	Height (mm)			
	D6	D12	D16	average
a	1050	1050	1150	1080
b	980	950	1000	980
c	1150	1100	1150	1130
f	1200	1200	1250	1220
e	1250	1250	1250	1250
			lsd (p=0,05)	49
			(p=0,01)	66

The results of the statistical analysis indicated that water stress during any of the vegetative growth stages (stages a, b and c) reduced final plant height significantly (Table 3.20). This is contradictory to the results obtained with wheat where only the plants stressed during the late vegetative stages were significantly shorter than those of the control plots. Wheat plants which were stressed during the early vegetative stages recuperated the loss and ended up comparable in size to those on the control plots.

TABLE 3.20 - Differences between final length means of durum wheat stressed at different growth stages (1987 season)

Growth stages	b	a	c	f
e	270**	170**	120**	30
f	240**	140**	90**	
c	150**	50*		
a	100**			

** = significant at 1% level
* = significant at 5% level

The ears of the plants on the a and b-plots came out about a week earlier than on the other plots. This phenomenon was also observed during previous experiments with wheat and it seemed to be a reaction for survival by the plant when submitted to soil water stress. The plant will ensure the survival of the species by producing the seeds before it dies.

The influence of soil water stress on the grain yield is illustrated in Table 3.21. Yields obtained from the plots where water stress was induced during the vegetative growth stages (stages a, b and c) were significantly lower than those of the control plots and those of the f-plots where stress was induced after flowering stage (Table 3.22). The highest yields were obtained at site D16 where also the deepest effective root system was found. For every treatment the yield at site D16 was higher than the respective average of the three sites D6, D12 and D16. The lowest yields were obtained from the plots where water stress was induced during the appearance of the flag leaf (b-plots).

TABLE 3.21 - Grain yields of durum wheat harvested at sites D6, D12 and D16 (1987 season)

Plot	Grain yield (ton/ha)			
	D6	D12	D16	average
a	3,70	2,81	4,55	3,69
b	2,33	2,83	3,99	3,05
c	4,05	3,33	4,38	3,92
f	4,71	4,59	5,49	4,93
e	4,55	4,77	5,06	4,79
			lsd (p=0,05)	0,78

TABLE 3.22 - Differences between grain yield means of durum wheat stressed at different growth stages (1987 season)

Growth stages	b	a	c	e
f	1,78*	1,15*	0,91*	0,04
e	1,74*	1,11*	0,87*	
c	0,87*	0,24		
a	0,64			

* = significant at 5% level

3.2.3 Maize

The growth stages at which the drying cycles were started during the 1985-1986 and 1986-1987 summer seasons are summarized in Table 3.23. The *e* plots were used as well-watered control plots and were irrigated when 40% of PAWC was extracted. For the 1985-1986 summer season a PAWC value was calculated by means of the model developed by Boedt & Laker (1985). It was impossible to determine a PAWC value for the young growth stages before the start of the experiments, but a maximum extraction of 40% of PAWC ensured that the plants did not experience water stress at any growth stage. For the 1986-1987 season the PAWC values which were found during the 1985-1986 season were used.

TABLE 3.23 - Phenological growth stages at which the drying cycles were started during the 1985-1986 and 1986-1987 summer seasons at sites D6, D12 and D16

Plot no.	Phenological stage	Days after planting
1985-1986		
a	4-leaf	27
b	8-leaf	42
c	12-leaf	62
f	silking	80
1986-1987		
a	4-leaf	27
b	6-leaf	37
c	8-leaf	47
d	12-leaf	57

3.2.3.1 Summer 1985-1986

During this season the plants were severely damaged by hail and leaf expansion measurements could not be conducted.

3.2.3.1.1 Pre-dawn leaf water potential patterns

The PLWP patterns found on plots D6a, D6b, D6c and D6f are illustrated in Figure 3.40. FMS was clearly indicated on all plots. On plot D6a PLWP values were very constant at -150kPa during the first 15 days of the drying cycle, after which they started to oscillate while decreasing gradually to about -600kPa. FMS was observed on day 35 of the drying cycle (i.e. at 12-leaf stage) when PLWP dropped sharply to -1250kPa. This drop was followed by

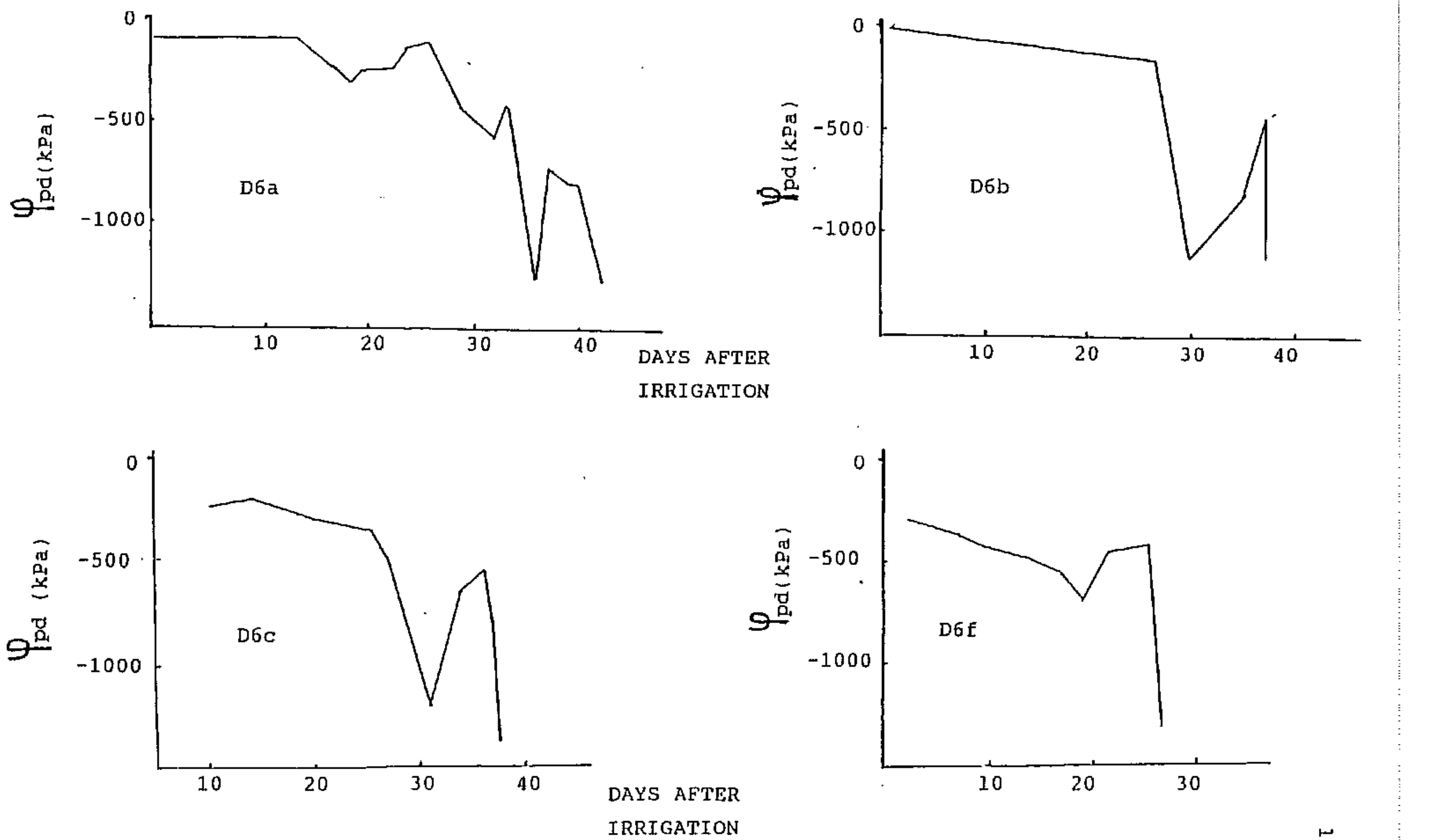


FIG.3.40 PRE-DAWN LEAF WATER POTENTIAL PATTERNS OF MAIZE AT SITE D6 (1985-1986 SEASON)

the fluctuating phase caused by a periodic recovery of the plants. On plot D6b PLWP remained high until day 27 of the drying cycle, after which it dropped sharply to -1100kPa on day 30, indicating FMS, and the fluctuating phase was started (16-leaf stage). On plot D6c FMS was indicated by the drop in PLWP to -1400kPa on day 30 of the drying cycle (silking stage). A cycle of temporary recovery of the plants followed. On plot D6f FMS, indicated by the sharp drop in PLWP to -1350kPa, was observed on day 27 of the drying cycle (grain filling stage).

The PLWP patterns for sites D12 and D16 are presented in Appendices 3.2.20 and 3.2.21. The patterns were similar to those found at site D6. The number of days to reach FMS and the phenological growth stages at which FMS was observed are listed in Table 3.24.

TABLE 3.24 - Number of days to reach FMS and phenological growth stage at which FMS was observed at sites D6, D12 and D16 (1985-1986 season)

Plot no.	Phenological stage	Days to reach FMS
D6a	12-leaf	35
D6b	16-leaf	30
D6c	silking	31
D6f	grain filling	27
D12a	12-leaf	35
D12b	16-leaf	31
D12c	silking	29
D12f	grain filling	28
D16a	12-leaf	35
D16b	16-leaf	30
D16c	silking	33
D16f	grain filling	31

3.2.3.1.2 Leaf temperature and stomatal conductance

The diurnal course of photosynthetically active radiation (PAR), leaf and air temperature, water vapour saturation deficit (VSD) and stomatal diffusion conductance (gs) measured on different days at site ISO-B on plots with different soil water status during two short periods of this season is presented in Figure 3.41. During the first week (14-17 January 1986) typical diurnal patterns of incoming PAR and net radiation were observed. On day 28 and 29 January cloudy overcast conditions resulted in fluctuating PAR patterns. Levels of PAR rose to almost 2,5 mmol/sq.m.sec. by mid-day and noon air temperatures ranged between 25 and 37 °C. Leaf temperatures followed

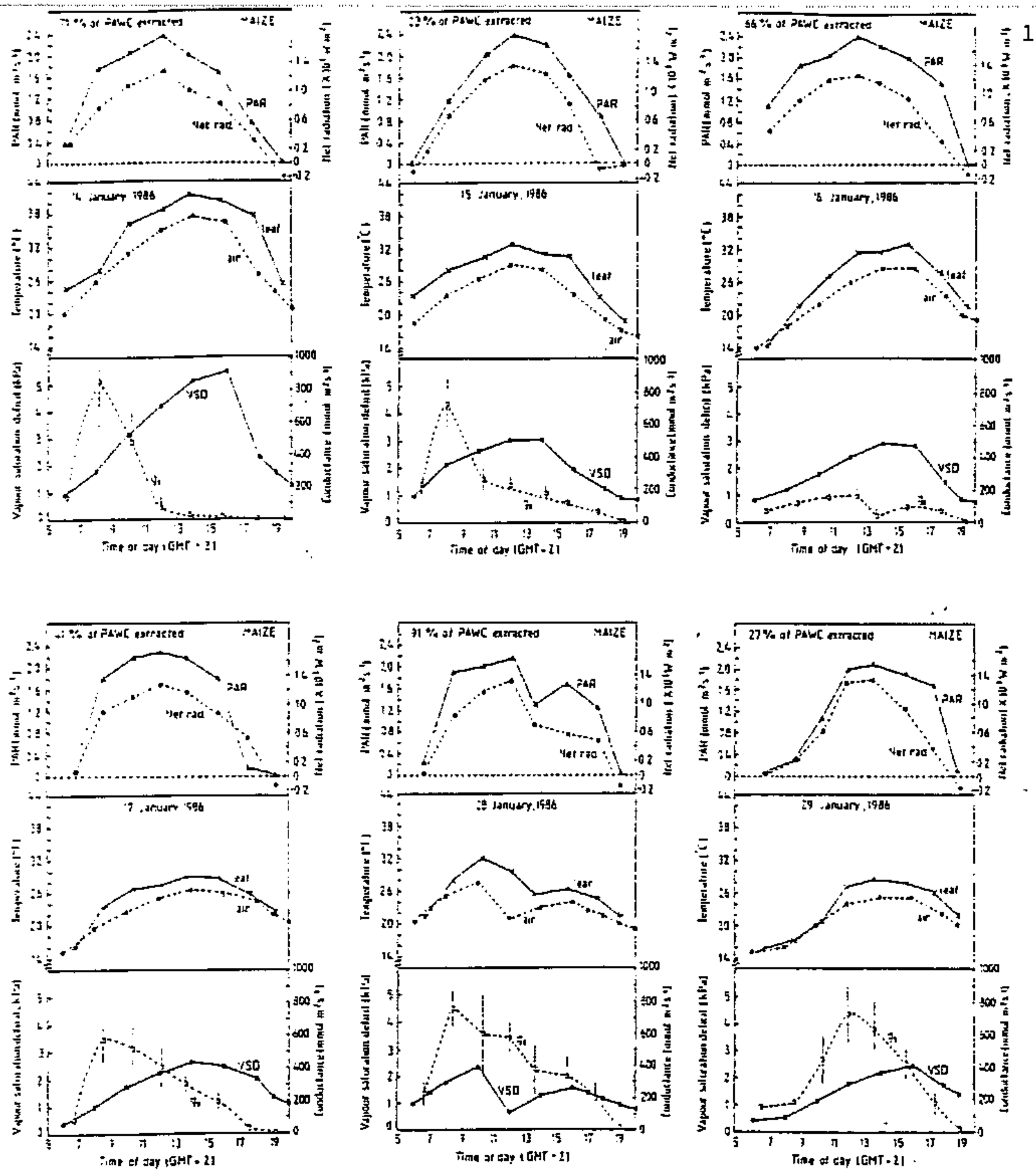


FIG. 3.41 Diurnal course of photosynthetically active radiation (PAR), leaf and air temperature, water vapour saturation deficit (VSD and stomatal diffusion conductance (gs) of maize leaves (1985-1986 season). The soil water status has been indicated in terms of percentage of PAWC. Figures for total net radiation balance (net rad.) refer to an adjacent short grassland vegetation. Vertical bars are +/- SE. From Ceulemans et al.(1988b).

exactly the same pattern as the atmospheric temperatures, but were 1 to 4 °C higher than the corresponding air temperatures.

On all days of measurement, except 16 January, gs increased very sharply to peak in the early morning and then immediately started decreasing. On the cloudless mornings (14, 15, 17 and 28 January) gs reached its peak at 0800h after which it decreased. This rapid increase coincided with rapid increases in radiation as well as increases in air and leaf temperatures and VSD. On 29 January, gs started rising sharply at 0800h and only reached its peak at 1200h after which it started to decrease. On this day radiation, leaf and air temperatures and VSD all remained low until 0800h. On 16 January, gs remained at very low levels throughout the day, PAR, leaf and air temperatures and VSD values were, however, normal on that day and can, therefore, not be responsible for the low gs values. These low gs values can only be explained by the fact that this day followed upon two days characterized by very demanding climatic conditions which resulted in a sharp decrease of gs immediately after the early morning peak.

Two basic patterns of decrease in gs after the morning peak were observed. The first pattern (17, 28 and 29

January) shows a linear decrease in gs from the morning peak to zero at about 1900h. The second pattern (14 and 15 January) consists of a very sharp decrease in gs immediately after the early morning peak. On 14 January, air and leaf temperatures and VSD were very high and gs decreased linearly to reach an extremely low value at 1200h, after which it decreased slowly to zero at 1700h. On 15 January, gs decreased as sharply as on the previous day from 0800h to 1000h, after which it decreased slowly to zero at 1900h.

The peak gs value for each of the five days was related to the air temperature at the time that the peak value was recorded. Furthermore, a highly significant linear relationship between air temperature and gs at 0800h was found. Therefore, early morning air temperature seemed to be an important factor for controlling gs in maize during the morning. Although there were large differences in soil water status on the different plots (from 23% to 91% of PAWC extracted), there was little evidence of decreased gs as a result of decreased water availability. Neither PAR saturated gs nor gs at solar noon or daily average gs showed a distinct relationship with the amount of soil water extracted over this range of plant available water. These can be taken as indications that plants were not yet subject to soil induced water stress at 91% extraction of PAWC. This supports the validity of the PAWC concept.

A comprehensive discussion of this study is given by Ceulemans et al. (1988b).

A second experiment during which well-watered and stressed plants were studied on the same day in order to obtain a more comprehensive picture of soil-induced versus atmospheric-induced water stress in maize plants is discussed in section 3.2.3.1.3.

3.2.3.1.3 Effects of soil water stress on stomatal diffusion conductance and leaf water potential

Stomatal conductance of unstressed plants responded in a classical way to increasing PAR and a rectangular hyperbola could be used to describe the conductance-PAR response curve (Figure 3.42). The diurnal pattern showed an almost consistent increase in gs from early morning until mid-day on the different days (Figure 3.43a). However, mid-day gs values differed markedly between the different days. This is probably the result of early morning environmental differences rather than mid-day environmental conditions. The mid-day stomatal conductance of unstressed plants is visualized in

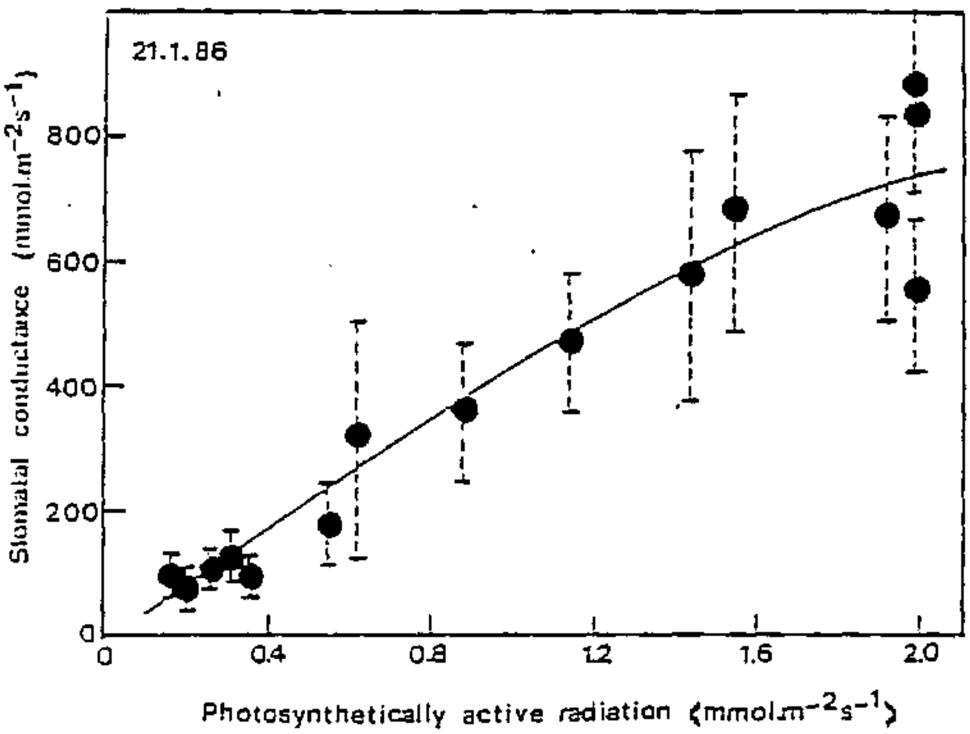


FIG. 3.42 The response of stomatal conductance to photosynthetically active radiation on the maize leaf surface for unstressed plants on a specific measuring day (January 21, 1986). Each point represents the mean of four measurements. Vertical bars represent standard error of mean. From Laker et al., 1988 (APPENDIX 3.4).

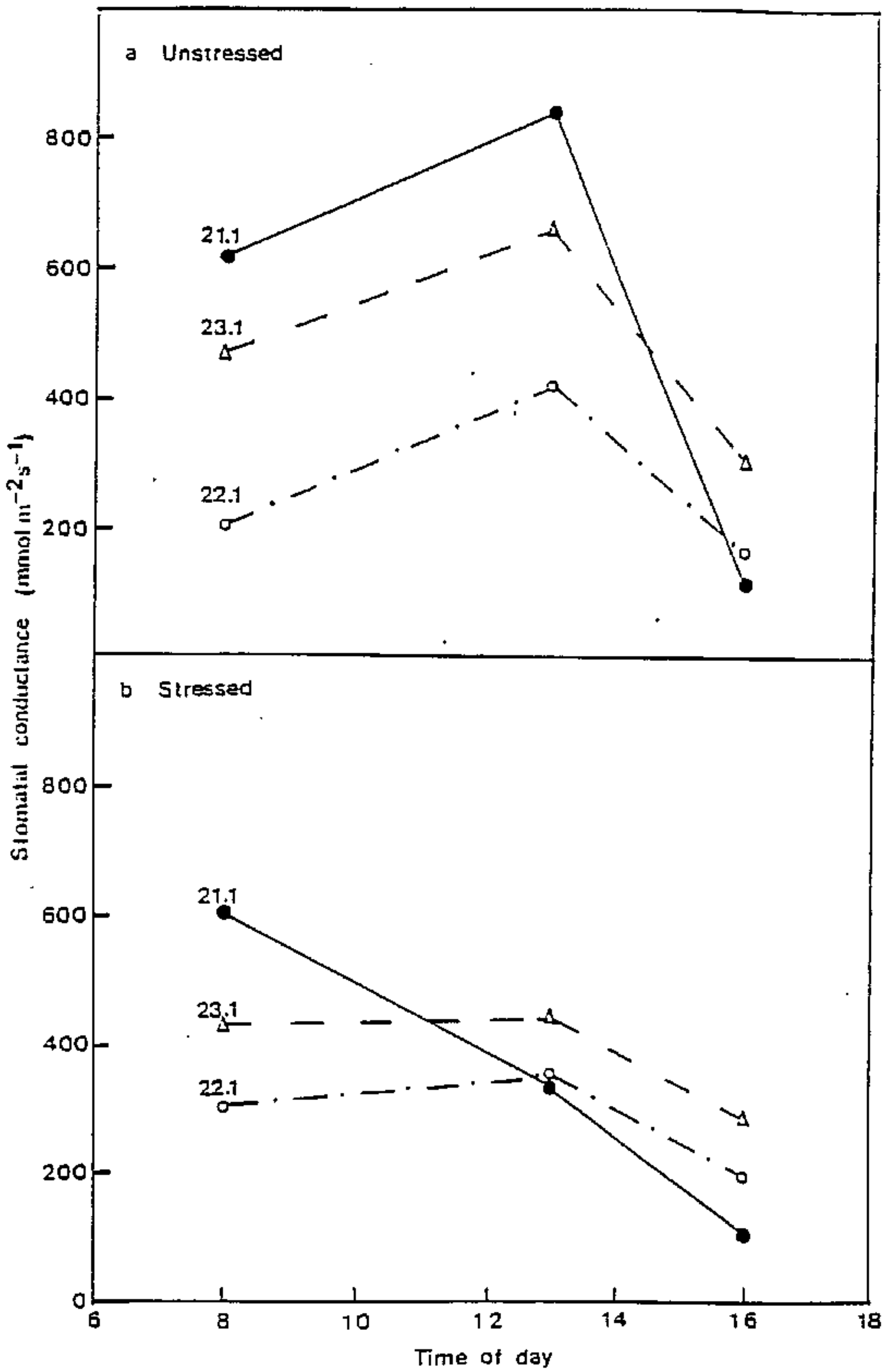


FIG. 3.43 Stomatal conductance values for stressed and unstressed maize plants respectively at three different times of the day on three consecutive measuring days (1985-1986 season). From Laker et al., 1988 (APPENDIX 3.4).

scenario A of Figure 3.44 which can be summarized as follows: sharp daily fluctuations in mid-day gs in response to differences in early morning environmental conditions (especially temperature and VSD).

In the case of the "stressed" plots, gs increased very slightly from early morning to mid-day on the day with a low early morning conductance. On the day with an intermediate early morning gs, conductance remained constant until mid-day. Finally, on the day with a high early morning conductance, gs dropped sharply (Figure 3.43b). This illustrates that the low soil water status is clearly a limiting factor resulting in the failure of the system to maintain a high gs after high early morning values. Consequently, the daily variations in mid-day gs were very small (scenario B of Figure 3.44).

Late afternoon gs values were, as in the case of the early morning values, independent of soil water status but closely related to VSD at the time of measurement (Figure 3.45). This was in contrast with the early morning values which were more closely related to air temperature than to VSD.

Early morning (0800h) leaf water potentials (LWP) were constant at about -1000kPa, irrespective of soil water

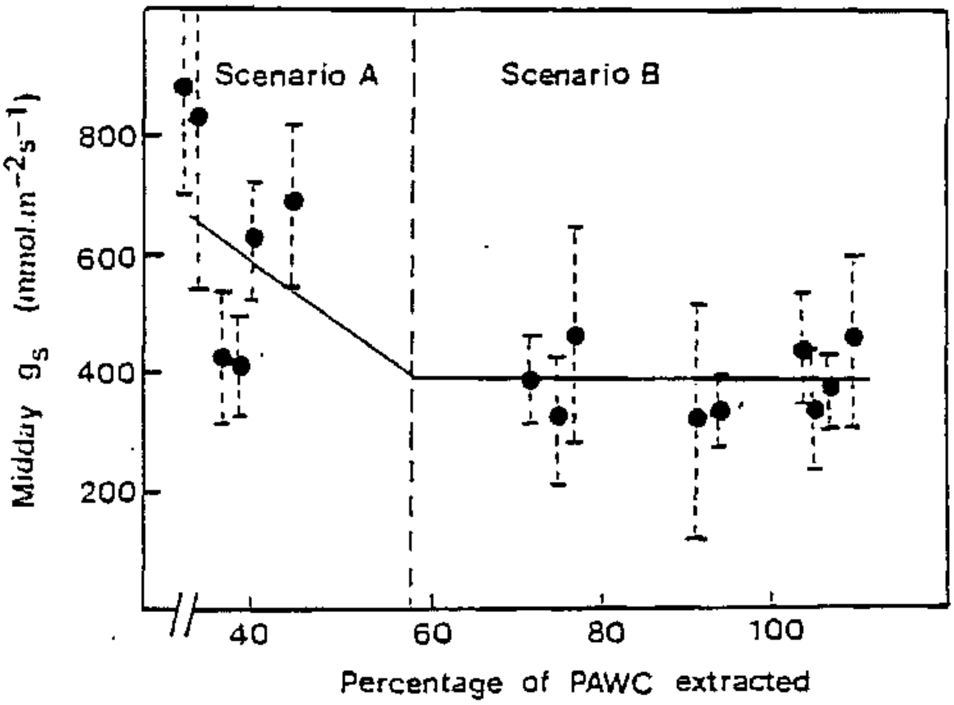


FIG. 3.44 Effects of increasing soil water stress on stomatal diffusion conductance of mature maize at midday in mid-summer (1985-1986 season). Each point is the mean of five measurements. Vertical bars represent standard error of mean. From Laker et al., 1988 (APPENDIX 3.4).

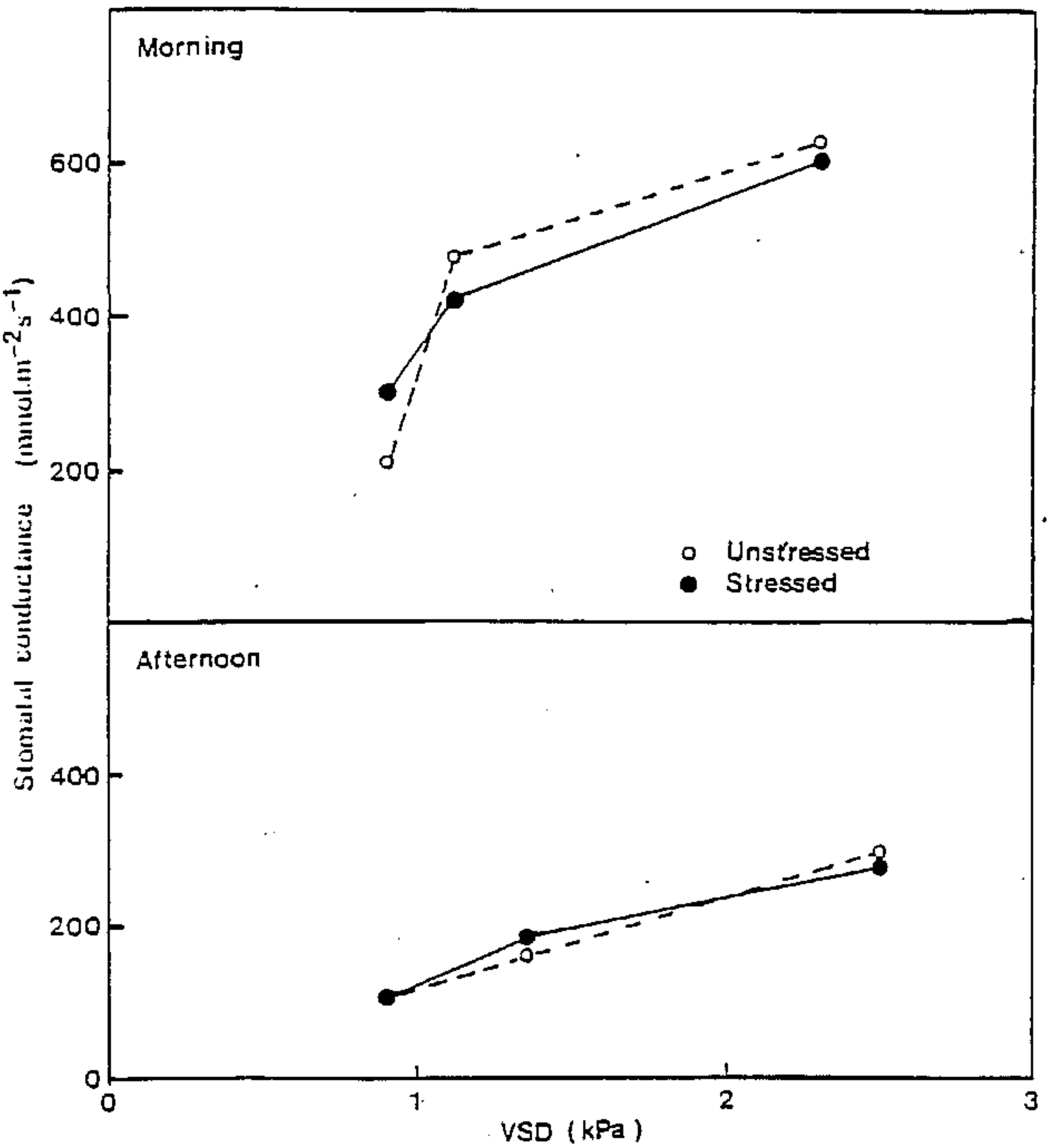


FIG. 3.45 Mean early morning and late afternoon stomatal conductance values as a function of VSD on three consecutive measuring days (1985-1986 season). From Laker et al., 1988 (APPENDIX 3.4).

status or environmental conditions. The value of -1000kPa seems very low for the unstressed plants, but is higher than would be expected for the "stressed" plants. The latter is probably a confirmation of the gs values which indicated that the "stressed" plants were still able to maintain a reasonable level of stomatal conductance. Since the "stressed" plants were on plots of which about 100% PAWC had been extracted, it again supports the validity of the PAWC concept, indicating that plants were not under severe stress.

For both stressed and unstressed plants LWP decreased sharply from early morning until mid-day but the mid-day patterns for stressed and unstressed plants differed markedly (Figure 3.46). In the case of the unstressed plants, mid-day LWP values were very different on the different days, similar to the pattern found for gs. Mid-day LWP was inversely related to early morning VSD and gs. On the day with the highest early morning VSD and gs, mid-day LWP decreased to -1800kPa, the same value as for the stressed plants. In the case of the stressed plants the mid-day values were almost constant at -1800kPa.

During the late afternoons LWP recovered as a result of decreases in VSD and gs. This recovery was less for the

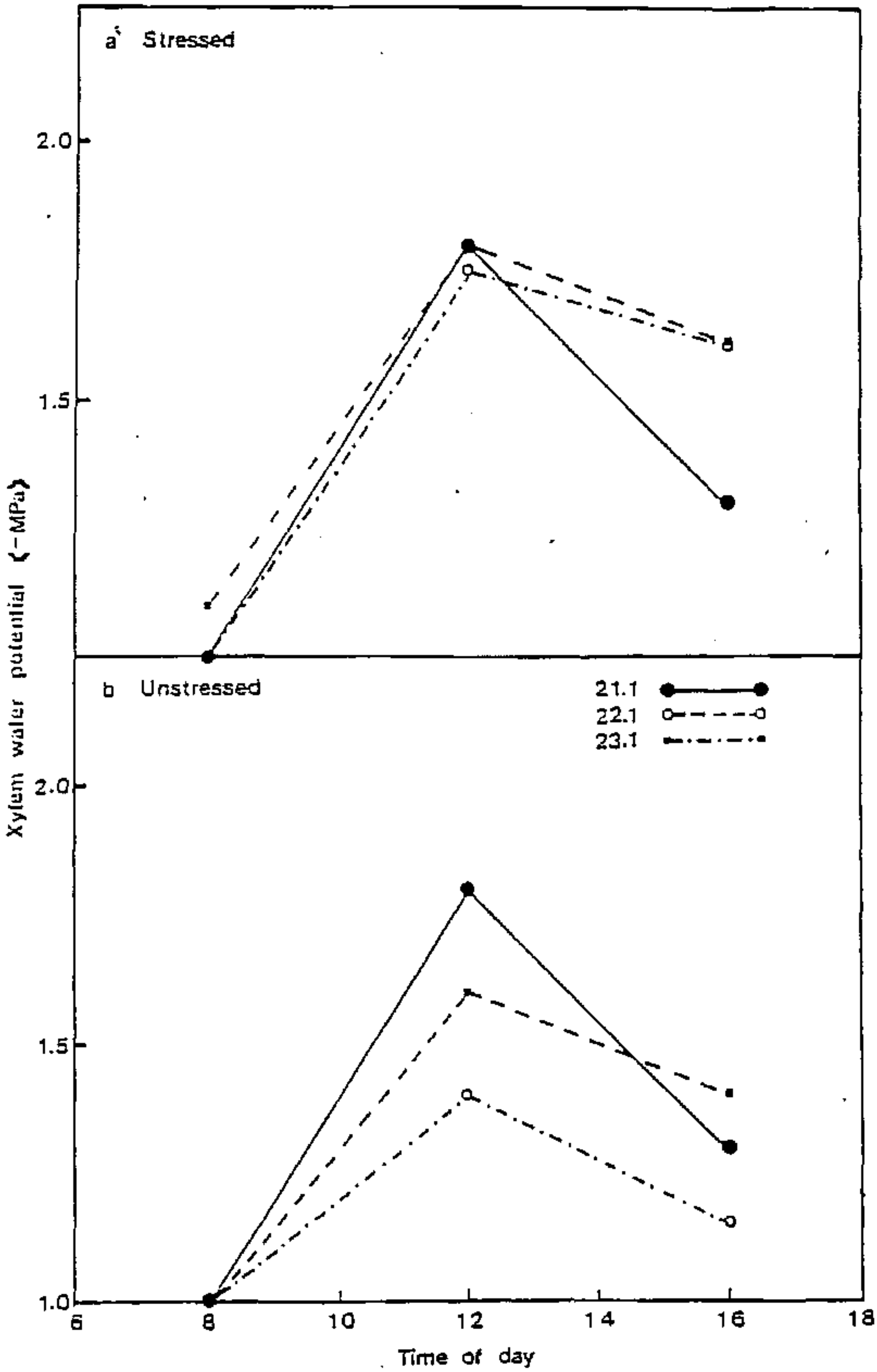


FIG. 3.46 Leaf (xylem) water potential (LWP) values for stressed and unstressed maize plants respectively at three different times of the day on three consecutive measuring days (1985-1986 season). From Laker et al., 1988 (APPENDIX 3.4).

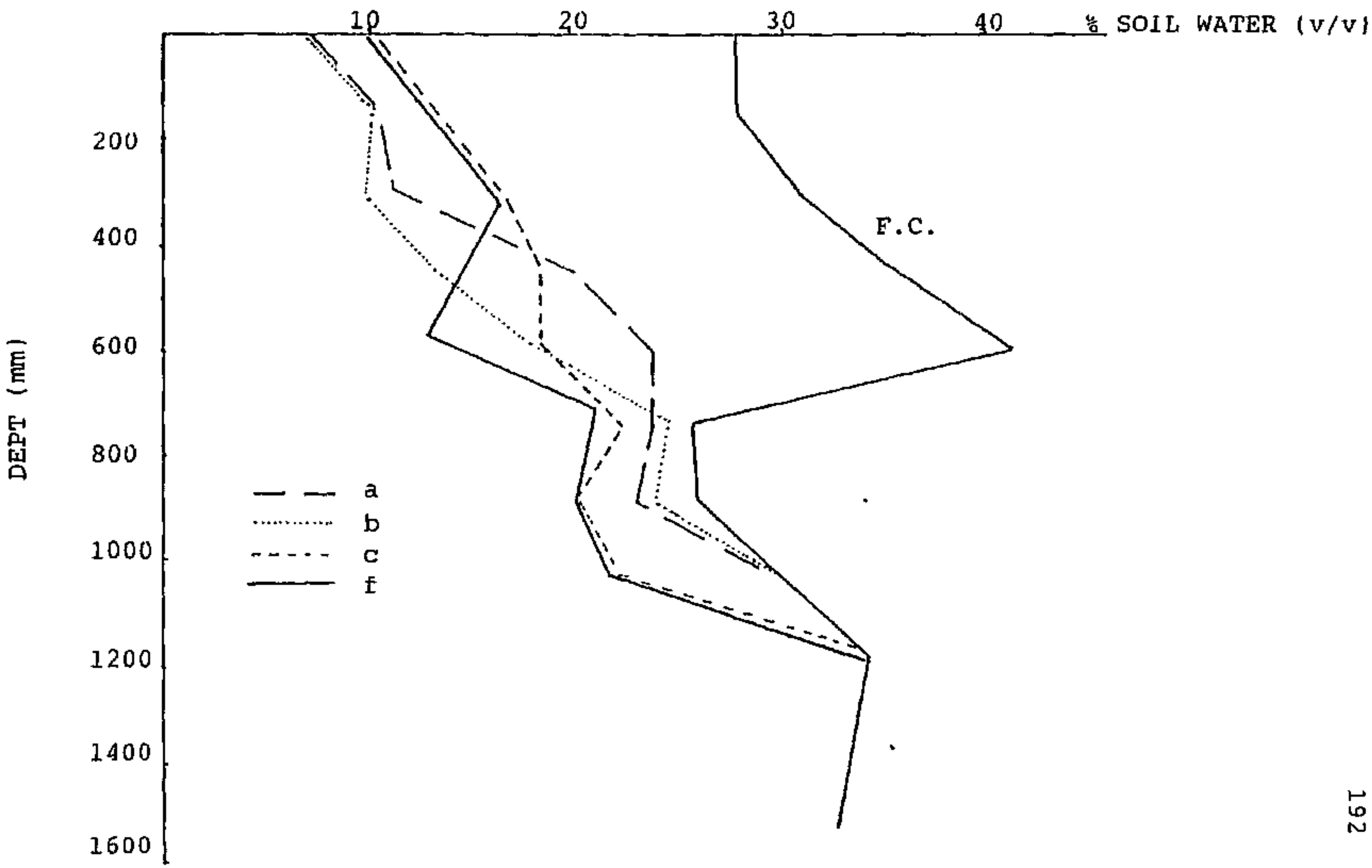
stressed plants than for the unstressed plants except on the day with the cloudy afternoon (January 21). On that day both stressed and unstressed plants reached identical LWP values. These late afternoon patterns indicated that the "stressed" plants, i.e. those at about 100% extraction of PAWC or FMS ("first material stress"), were in fact just starting to show indications of soil-induced water stress. This again supports the validity of the PAWC concept.

A comprehensive discussion of this study is given by Laker, Ceulemans & Vanassche (1988, Appendix 3.4).

3.2.3.1.4 PAWC values and soil water extraction patterns

The soil water extraction patterns for the different growth stages at site D6 are illustrated in Figure 3.47. The patterns showed the typical fan shape with a downward moving convergence point as the plants grew older. The convergence point, marking the lower boundary of the effective root zone was found at a depth of 1000mm for both stages a and b (12-leaf and 16-leaf stages). The extraction of soil water from layers deeper than 700mm was negligible up to the end of stage b (16-leaf stage). The soil water extraction pattern of plot D6c (silking stage) showed an increase in extraction from layers

FIG.3.47 SOIL WATER EXTRACTION PATTERNS OF MAIZE AT FIRST MATERIAL STRESS AT DIFFERENT GROWTH STAGES AT SITE D6 (1985-1986 SEASON)



deeper in the profile. However, the soil water extraction from soil layers deeper than 700mm was still less than 20% of the PAWC. At growth stage f (flowering and grain filling stage) more water was extracted from soil layers between 400mm and 700mm depth, resulting in a bulging to the left of the first stress line. The quantities of soil water extracted at different depths and the PAWC values for each growth stage are listed in Table 3.25.

TABLE 3.25 - Quantities of soil water extracted by maize at different soil depths and PAWC values for each growth stage at site D6 (summer 1985-1986)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	flowering
0- 100	18,3	18,0	15,8	15,0
100- 200	18,0	18,5	14,7	15,0
200- 300	19,8	20,7	14,6	16,3
300- 400	17,0	21,7	16,2	18,3
400- 500	16,5	22,5	19,5	24,3
500- 600	17,8	23,0	23,5	30,0
600- 700	6,0	7,2	9.5	12,5
700- 800	2,3	1,3	4,0	5,0
800- 900	4,2	1,7	6,0	6,3
900-1000	1,0	0,5	7,7	8,0
1000-1100			6,5	8,0
1100-1200				
PAWC	120,9	134,6	138,0	158,7

The patterns for site D12 are presented in Appendix 3.3.7. The basic shape is a fan with a convergence point at a depth of 1050mm at stages a and b (12-leaf and 16-leaf stages) and at a depth of 1200mm at stages c and f (silking stage and grain filling stage). More soil water was extracted from layers deeper in the profile than at site D6 because there was no compacted soil layer at this site and the roots could develop deeper in the profile. At growth stages a and b (12-leaf and 16-leaf stages) the portion of water extracted from soil layers deeper than 700mm was already 20% of the PAWC and this increased to 35% for stages c and f.(silking stage and grain filling stage stage). An increased soil water extraction from layers between 600mm and 900mm depth caused the first stress line to bulge out in this part of the profile. The quantities of soil water extracted at different soil depths and the PAWC values for each growth stage are listed in Table 3.26.

TABLE 3.26 - Quantities of soil water extracted by maize at different soil depths and PAWC values for each growth stage at site D12 (summer 1985-1986)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	flowering
0- 100	15,8	16,8	15,5	17,3
100- 200	16,8	17,6	15,5	16,1
200- 300	17,3	18,7	16.3	17,5
300- 400	12,4	12,8	9,0	12,3
400- 500	9,3	9,9	7,3	10,5
500- 600	8,6	9,2	10,0	11,3
600- 700	10,8	12,4	13,3	12,8
700- 800	11,1	12,3	13,5	12,5
800- 900	9,0	7,8	11,0	11,0
900-1000	2,5	2,5	10,8	11,0
1000-1100			9,0	10,8
1100-1200			4,0	4,0
1200-1300				
PAWC	113,6	120,0	135,2	147,1

The soil water extraction patterns found at site D16 are illustrated in Appendix 3.3.8. As in the case of wheat and durum wheat water was extracted from layers deep in the profile already at stage a (12-leaf stage). The first stress and field capacity lines were running more or less parallel, indicating a constant extraction per unit of depth. Going from stage a (12-leaf stage) to stage c (silking stage), the first stress line shifted to the left and the increase of the PAWC was due to a higher water extraction throughout the profile. The evolution of the soil water extraction pattern from stage c (silking stage) to stage f (flowering and grain filling stages) consisted in a further widening of the gap between first stress and field capacity lines in the deeper soil layers (below a depth of 700mm). The quantities of soil water extracted at different soil depths and the PAWC values at each growth stage are listed in Table 3.27.

The soil water extraction patterns of maize at each site were similar in shape to those found for wheat and durum wheat. This indicates that the shape of the pattern for these three grain crops is determined by the soil profile characteristics rather than by the nature of the crop. Hensley & De Jager (1982) and Boedt & Laker (1985) also found that soil water extraction patterns of wheat and maize were similar.

TABLE 3.27 - Quantities of soil water extracted by maize at different soil depths and PAWC values for each growth stage at site D16 (summer 1985-1986)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	flowering
0- 100	8,5	10,3	10,2	11,0
100- 200	7,5	9,3	9,5	9,8
200- 300	8,5	10,8	8,0	10,3
300- 400	12,5	14,8	12,5	12,8
400- 500	13,5	16,0	14,8	14,3
500- 600	11,2	14,0	14,8	14,0
600- 700	10,8	13,0	13,0	13,8
700- 800	9,3	11,5	11,0	13,0
800- 900	7,2	10,0	8,5	12,3
900-1000	7,2	8,8	8,5	12,0
1000-1100	6,5	7,3	8,0	10,3
1100-1200	4,8	4,8	6,8	7,5
1200-1300	5,0	3,0	5,3	6,3
1300-1400	4,5	1,0	2,3	4,0
1400-1500	3,0		1,5	1,5
1500-1600				
PAWC	120,0	134,6	134,7	152,9

PAWC values of maize were slightly higher than those of wheat at all three sites (Table 3.28). The average ratio of PAWC of wheat to PAWC of maize was 92% which shows that PAWC of both crops are comparable. Similar ratios were found by Hensley & De Jager (1982). The ratio of PAWC of wheat to PAWC of maize determined on a Jozini series soil in sealed plots at Fort Hare Farm during the 1976-1977 season was also 92% (Hensley & De Jager, 1982). Contradictory to these results were the PAWC values obtained at Vaalharts by Boedt & Laker (1985). They found that, although the PAWC of wheat and maize was comparable. the PAWC of wheat was in most cases higher than that of maize. They, however, did studies mainly on fine sandy soils which tend towards higher bulk densities and soil strengths. Under such conditions root development of maize is restricted more than that of wheat (Du Preez, Bennie & Burger, 1979).

TABLE 3.28 - PAWC values of wheat and maize at flowering stage at site D6, D12 and D16 (1985-1986 season)

Site	PAWC (mm)		ratio (%)
	wheat	maize	
D6	140	159	88
D12	140	147	95
D16	143	153	93

The evolution of the PAWC values was different to those found for wheat (1985 winter season) and durum wheat (1987 winter season), where the maximum value was reached at a young stage, especially in the case of durum wheat. For maize the maximum value was only reached at flowering stage and even the value found at stage c (silking stage) was considerably smaller (Figure 3.48). Estimation of the evolution of the root length index according to the model of Botha et al. (1983) also predicted a higher PAWC value at this stage. It, therefore, seems that root development was abnormally low. This can be explained by the fact that during the early vegetative stages (8-leaf stage)

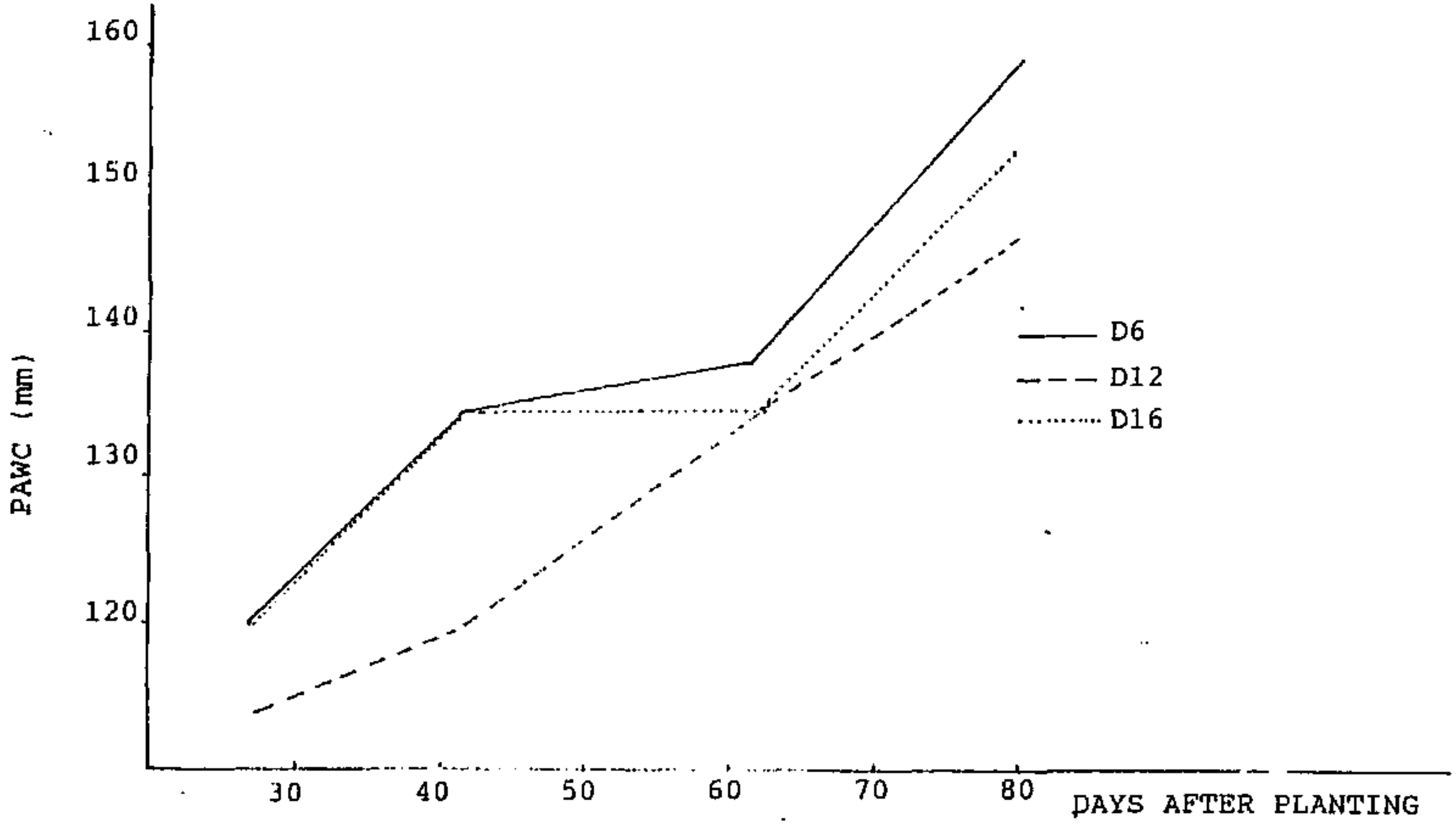


FIG.3.48 EVOLUTION OF PAWC VALUES OF MAIZE AT SITES D6, D12 AND D16
(1985-1986 SEASON)

the plants were severely damaged by a severe hailstorm. Less assimilates were available for transport to the roots due to the reduction of the photosynthetic area, resulting in a slower root growth and delay to reach the maximum PAWC value.

3.2.3.1.5 Effects of soil water stress on grain yield

Despite the fact that hail severly damaged the plants during the early vegetative stages, yields were quite high (Table 3.29). This is explained by the fact that the plants were quite young (8-leaf stage) at the time of the hail damage and had ample time to recuperate. Statistical analysis, using the analysis of variance for any number of treatments for a randomized complete block design (Steel & Torrie, 1980), of the yields indicated that there were no significant differences between the treatment means. This is contradictory to the results obtained by Denmead & Shaw (1960) who reported reductions of 25%, 50% and 21% in grain yield of maize caused by water stress during vegetative, silking and ear stages respectively. Similar reductions were also found by Robins & Domingo (1953).

TABLE 3.29 - Grain yield of maize, with a moisture content of 12.5 %, harvested at sites D6, D12 and D16 (1985-1986 season)

Grain yield (ton/ha)

Plot	D6	D12	D16	average
a	11,39	9,63	9,71	10,24
b	9,16	10,18	11,69	10,34
c	13,33	9,52	11,24	11,36
f	7,08	9,37	11,11	9,19
e	9,27	10,59	9,41	9,76
			lsd (p=0,05)	ns

3.2.3.2 Summer 1986-1987

3.2.3.2.1 Leaf expansion and pre-dawn leaf water potential patterns

The drying cycle on the a plots was started 27 days after planting, i.e. at the 4-leaf stage. The leaf area of the plants on plot D6a exceeded that of control plot D6e until day 35 of the drying cycle, i.e. 62 days after planting at 12-leaf stage (Figure 3.49). The leaf expansion rate on plot D6a dropped below that on D6e on day 22 of the drying cycle, i.e. 49 days after planting at 8-leaf stage (Figures 3.50). However, leaf expansion rates on plots D6b, D6c and in a lesser degree D6d, which were all also well-watered at that time, were also lower relative to that on the control plot (Figures 3.53, 3.56 and 3.59). It was therefore not D6a that slowed down, but the plants on D6e that grew abnormally fast during those

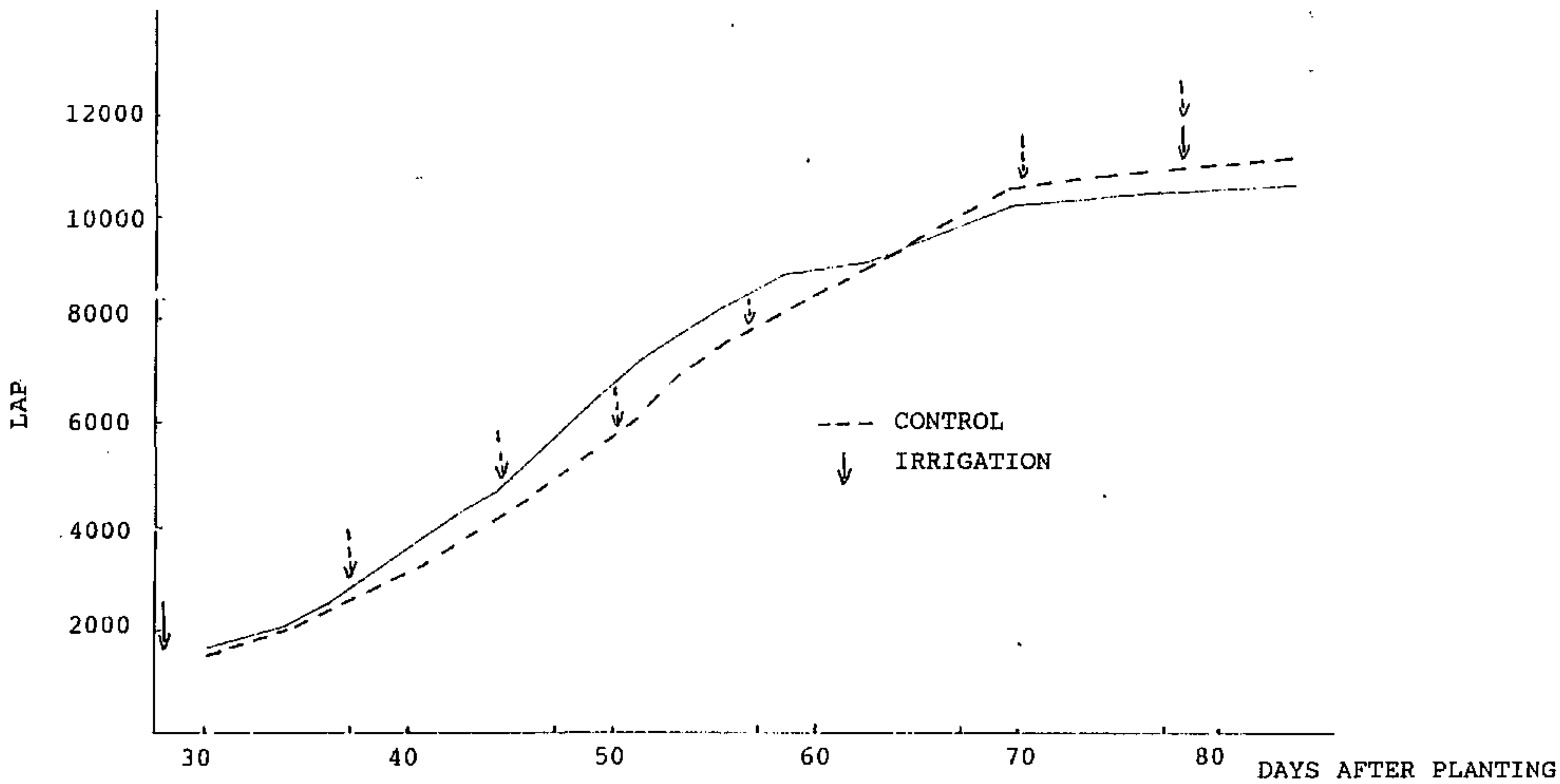


FIG.3.49 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT D6a (1986-1987 SEASON)

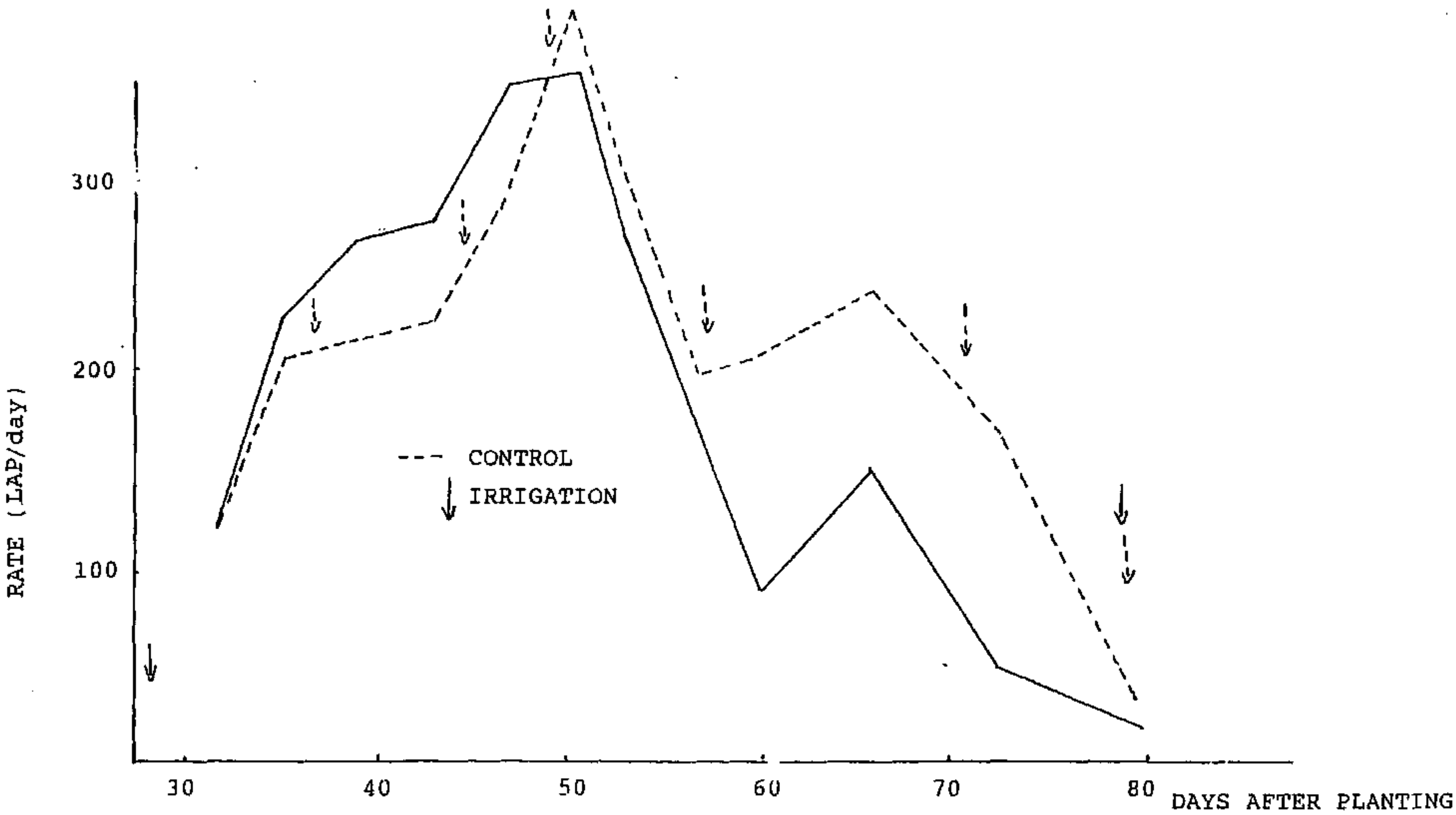


FIG.3.50 LEAF EXPANSION RATE OF MAIZE ON PLOT D6a (1986-1987 SEASON)

few days. Then on day 26 the leaf expansion rate on D6a slowed down sharply relative to D6e while the rate on plots D6b, D6c and D6d kept up with that of plot D6e. By day 33 of the drying cycle the leaf expansion rate of the plants on plot D6a dropped to about 50% of the rate measured on control plot D6e and remained that low. Similar to the results obtained during previous experiments with wheat, this day was taken as the critical date for FMS (12-leaf stage). Although the leaf expansion rate dropped markedly on day 33 of the drying cycle, PLWP failed to indicate FMS. PLWP dropped to -800kPa on day 30 of the drying cycle, but recovered to high values again thereafter. Only on day 40 of the drying cycle PLWP dropped sharply to -1200kPa, which would normally be taken to indicate FMS (Figure 3.51). This was far too late and plants were already experiencing severe soil water stress as was indicated by their physical appearance (Chapter 2).

The difference between the cumulative leaf expansion patterns of plots D12a and D12e at the end of the drying cycle was very clear. Until day 36 of the drying cycle the patterns were similar (Appendix 3.1.28). The leaf expansion rate on plot D12a started decreasing relative to that of the control plot on day 20 of the drying cycle. It was only on day 36 of the drying cycle that the

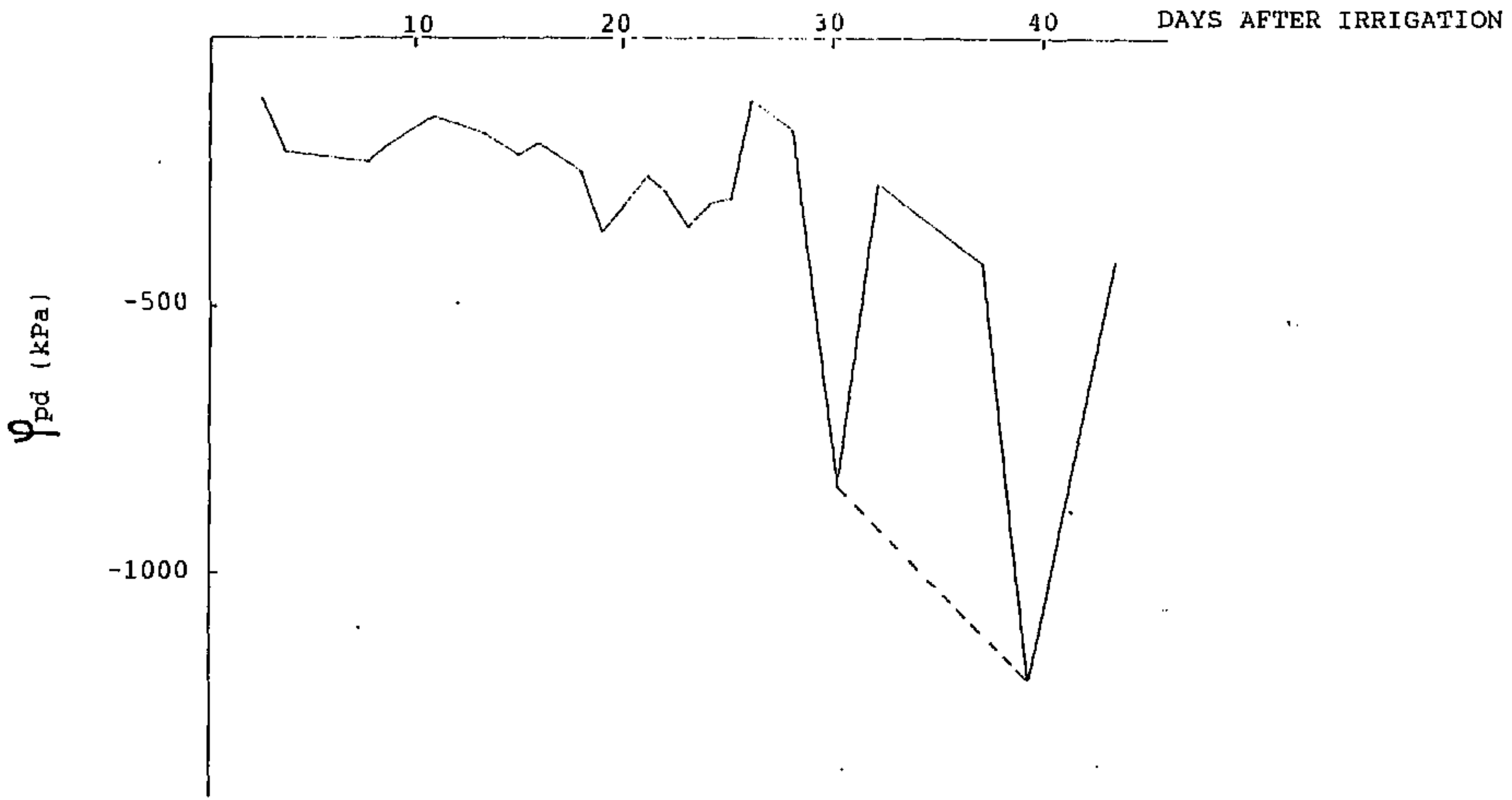


FIG.3.51 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE ON PLOT D6a (1986-1987 SEASON)

leaf expansion rate on D12a started decreasing sharply below that of the control plot (Appendix 3.1.29). PLWP decreased sharply to -700kPa on day 30 of the drying cycle, followed by a further sharp drop to below -1000kPa on day 40. The latter was too late to be taken as an indication of FMS (Appendix 3.2.22).

The difference in leaf expansion between plots a and e at site D12 was larger than at site D6. This was also observed with wheat during the 1985 and 1986 winter experiments and was explained by the high amount of water in the upper soil layers at site D6 as a result of a compacted soil layer at a depth of 600mm. This leads to less severe stress at site D6.

The decrease of the cumulative leaf expansion at the end of the experiments was caused by necrosis of the plant tissue to such an extent that the loss of material was higher than the formation of new material. This was also more explicit at site D12 than it was at site D6. Comparison with the cumulative leaf expansion pattern of plot D12e showed that the necrosis was faster at plot D12a as a result of the severe soil water stress experienced earlier (Appendix 3.1.28). This was supported by the fact that even upon irrigation the rate of loss of material did not decrease.

The drying cycle on the b plots was started 37 days after planting (6-leaf stage). The leaf expansion rate of the plants on plot D6b was somewhat slower than the rate measured on control plot D6e throughout the whole season (Figures 3.52 and 3.53). Between days 12 and 18 of the drying cycle the growth rate on D6b was much smaller than on D6e, but thereafter the two rates became practically identical again. Comparison with leaf expansion rates patterns on plots D6a, D6c and D6d indicated that it was in fact the plants on plot D6e that were growing abnormally fast between days 12 and 18. Then, on day 29 of the drying cycle, the rate on plot D6b dropped sharply relative to the control plot, indicating FMS. Two drops in PLWP were observed during the drying cycle (Figure 3.54). The first drop was measured 29 days after the start of the drying cycle when the values decreased sharply to -850kPa. The plants recovered during the following days but did not reach the same values as before day 29. This temporary recovery was followed by a second drop to -1200kPa on day 36 (16-leaf stage) which was far too late. FMS was identified by the drop in PLWP to -850 kPa on day 29 of the drying cycle, i.e. at 14-leaf stage, which coincided with the sharp decrease in leaf expansion rate.

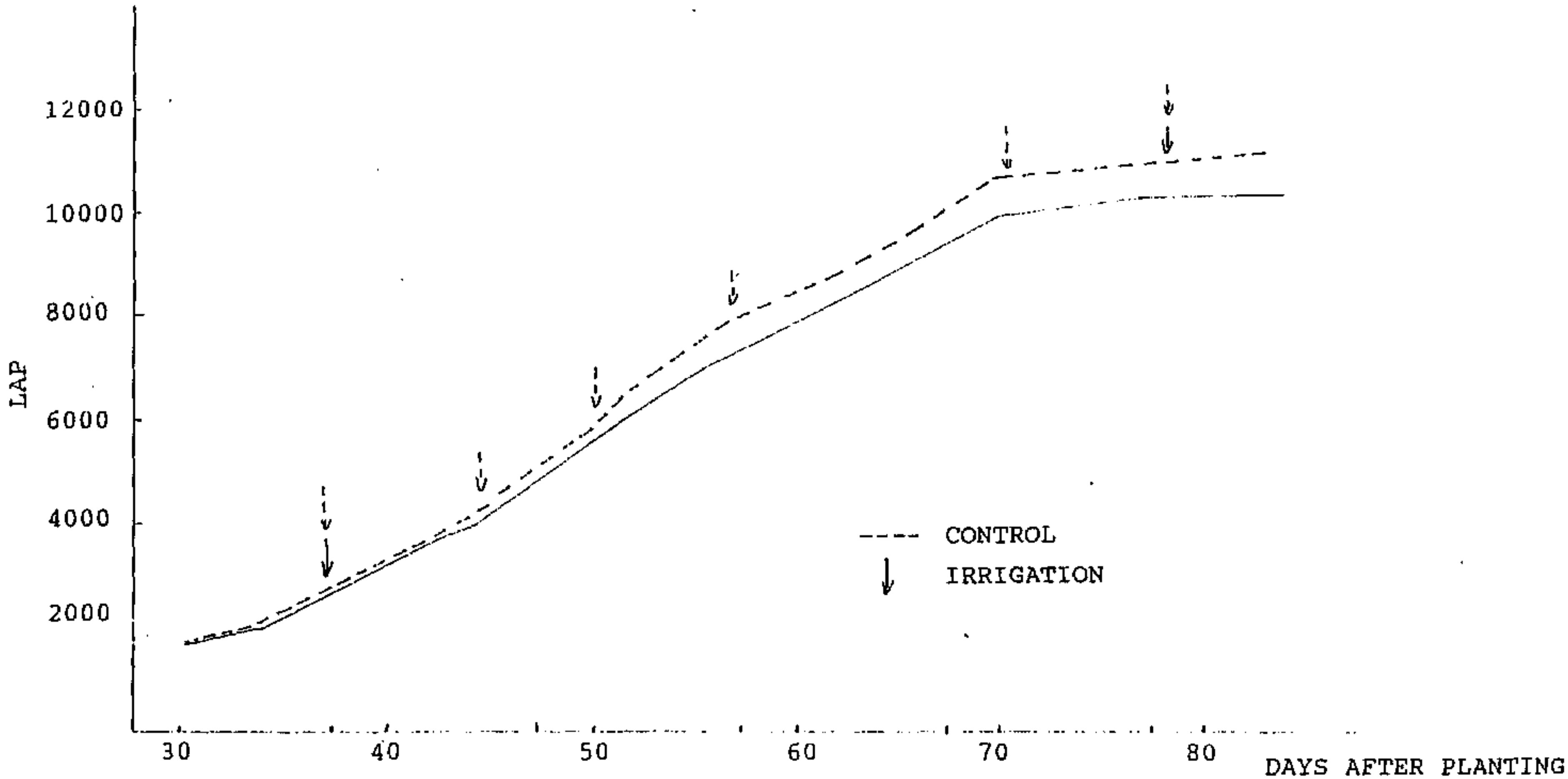


FIG. 3.52 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT (1986-1987 SEASON)

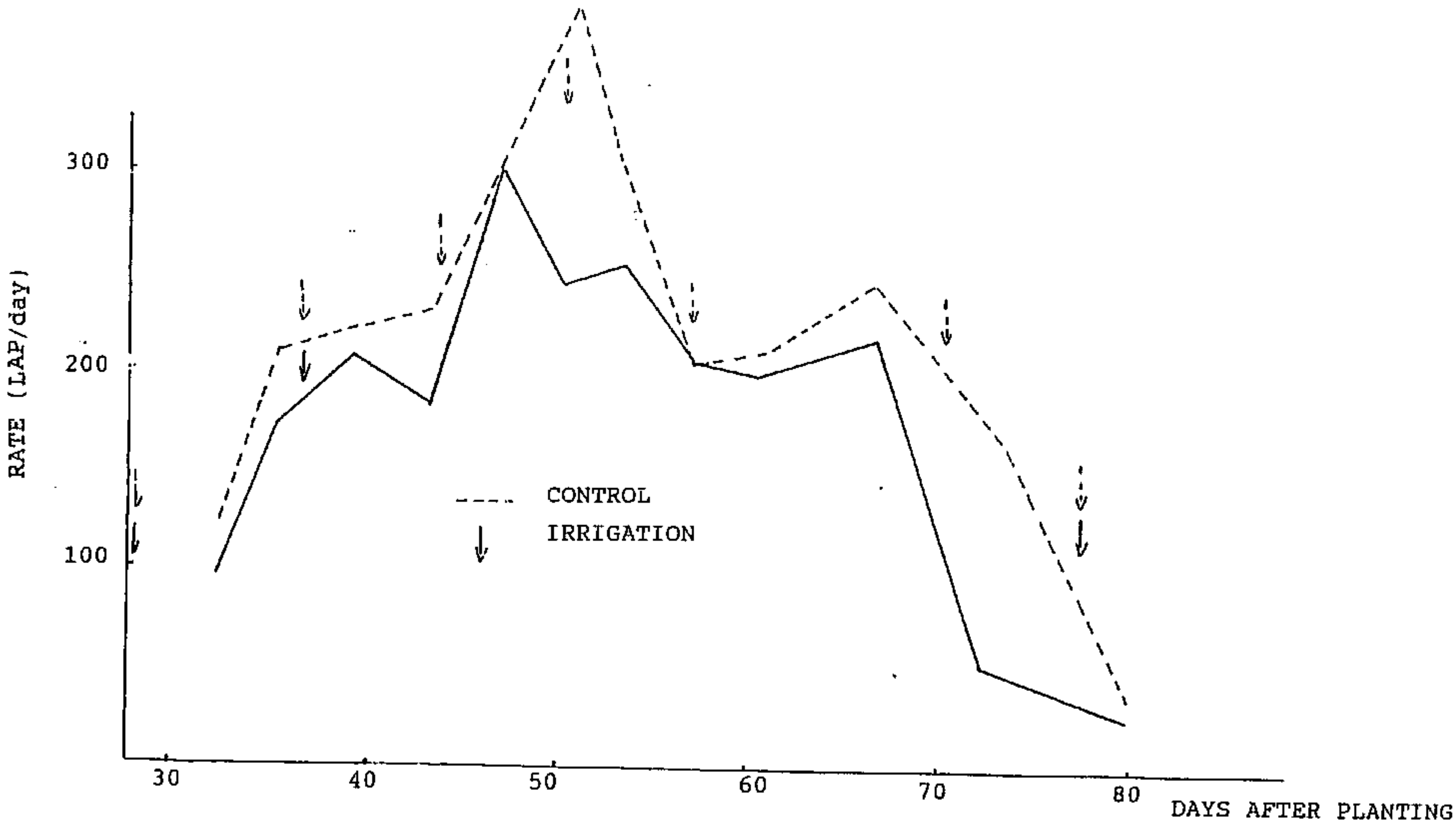


FIG.3.53 LEAF EXPANSION RATE OF MAIZE ON PLOT D6b (1986-1987 SEASON)

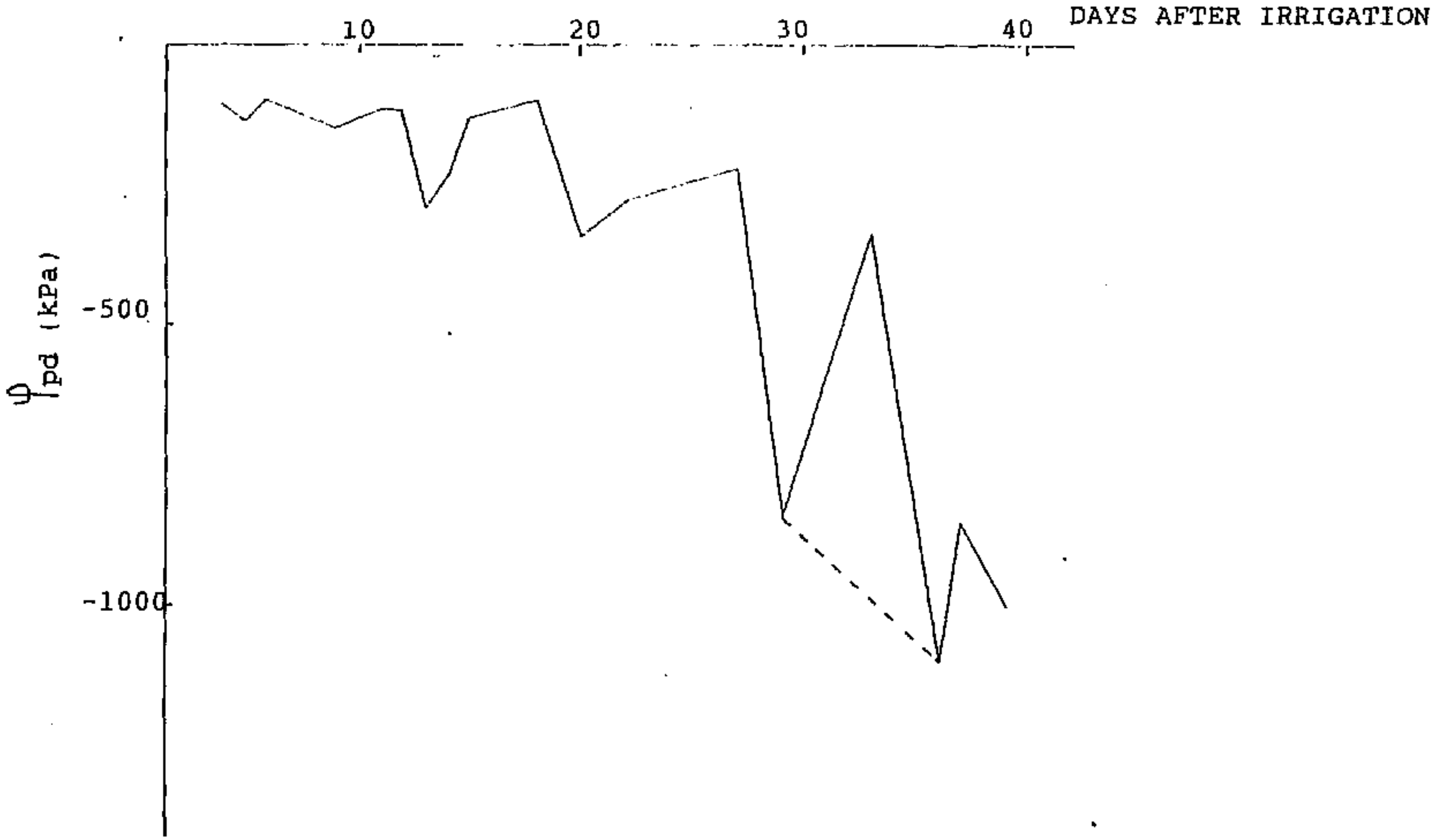


FIG.3.54 PRE-DAWN LEAF WATER POTENTIAL OF MAIZE ON PLOT D6b (1986-1987 SEASON)

The cumulative leaf expansion pattern of plot D12b showed a decrease in growth 20 days after the start of the drying cycle. This was clearly indicated in the leaf expansion rate pattern (Appendices 3.1.30 and 3.1.31). However, no indication of FMS could be found: five days later the leaf expansion rate was at a normal level again and exceeded the rate of the control plot during a few days. Then, after day 29 of the drying cycle, leaf expansion rates on plot D12b dropped sharply to about 30% of the rate on the control plot (on day 72 after planting, i.e. day 35 of the drying cycle). The drop in PLWP to -1200kPa on day 29 of the drying cycle, which coincided with the sharp decrease in leaf expansion rate, was taken as the indication of FMS (Appendix 3.2.23).

The effects of soil water stress on leaf expansion were smaller than during stage a during this stage and again they were less explicit at site D6.

On plot D12b the loss of material was bigger than the gain of new material near the end of the growing season. The resulting "negative" growth started about a week later than on plot D12a on which the drying cycle was started ten days earlier (Appendices 3.1.29 and 3.1.31). The effect of soil water stress on necrosis seems to be irreversible as even after irrigation on plot D12b the growth was still negative.

The results of PLWP and leaf expansion measurements on plots a and b at sites D6 and D12 are summarized in Table 3.30. From these data it is clear that the classical concept of FMS, which uses a critical PLWP value smaller than -1000kPa to detect FMS, is not applicable during young growth stages (i.e. before the 14-leaf stage).

The results suggest that during young growth stages a critical PLWP value of -800kPa should be used to define FMS. From the 14-leaf stage onwards a drop in PLWP to less than -1000kPa is interpreted as an indication of the onset of FMS.

TABLE 3.30 - Days on which the drop in PLWP and leaf expansion was measured on the a, b and c plots at sites D6 and D12 (1986-1987 season)

Plot	PLWP		Leaf expansion	Growth stage
	day	value (kPa)	day	
D6a	30	-800	31	12-leaf
D6b	29	-850	28	14-leaf
D6c	28	-1200	n.a.	16-leaf
D12a	30	-700	25	10-leaf
D12b	29	-1200	28	14-leaf
D12c	25	-1200	25	16-leaf

The drying cycles on plots D6c and D12c were started 47 days after planting (8-leaf stage). The leaf expansion pattern of plot D6c did not indicate FMS. The pattern was identical to that on control plot D6e until maturity was reached (Figures 3.55 and 3.56). Soil water stress at this stage, therefore, had no effect on leaf expansion. FMS was indicated by the drop in PLWP to a value of -1200kPa on day 28 of the drying cycle, i.e. at 16-leaf stage (Figure 3.57).

The cumulative leaf expansion on plot D12c was identical to that of the control plot until day 18 of the drying cycle, i.e. 65 days after planting (Appendix 3.1.32). The leaf expansion rate on plot D12c started decreasing sharply relative to that of the control plot 19 days after the start of the drying cycle (Appendix 3.1.33). It reached a very low level on day 26 of the drying cycle (day 73 after planting). PLWP indicated FMS on day 25 of the drying cycle, when the values dropped very sharply from -300kPa to -1200kPa and stayed below -1000kPa (Appendix 3.2.24).

The drying cycle on the d plots was started 57 days after planting. Soil water stress did not have any effect on the leaf expansion of the plants on plot D6d since the plants reached the fully grown stage within about 15 days

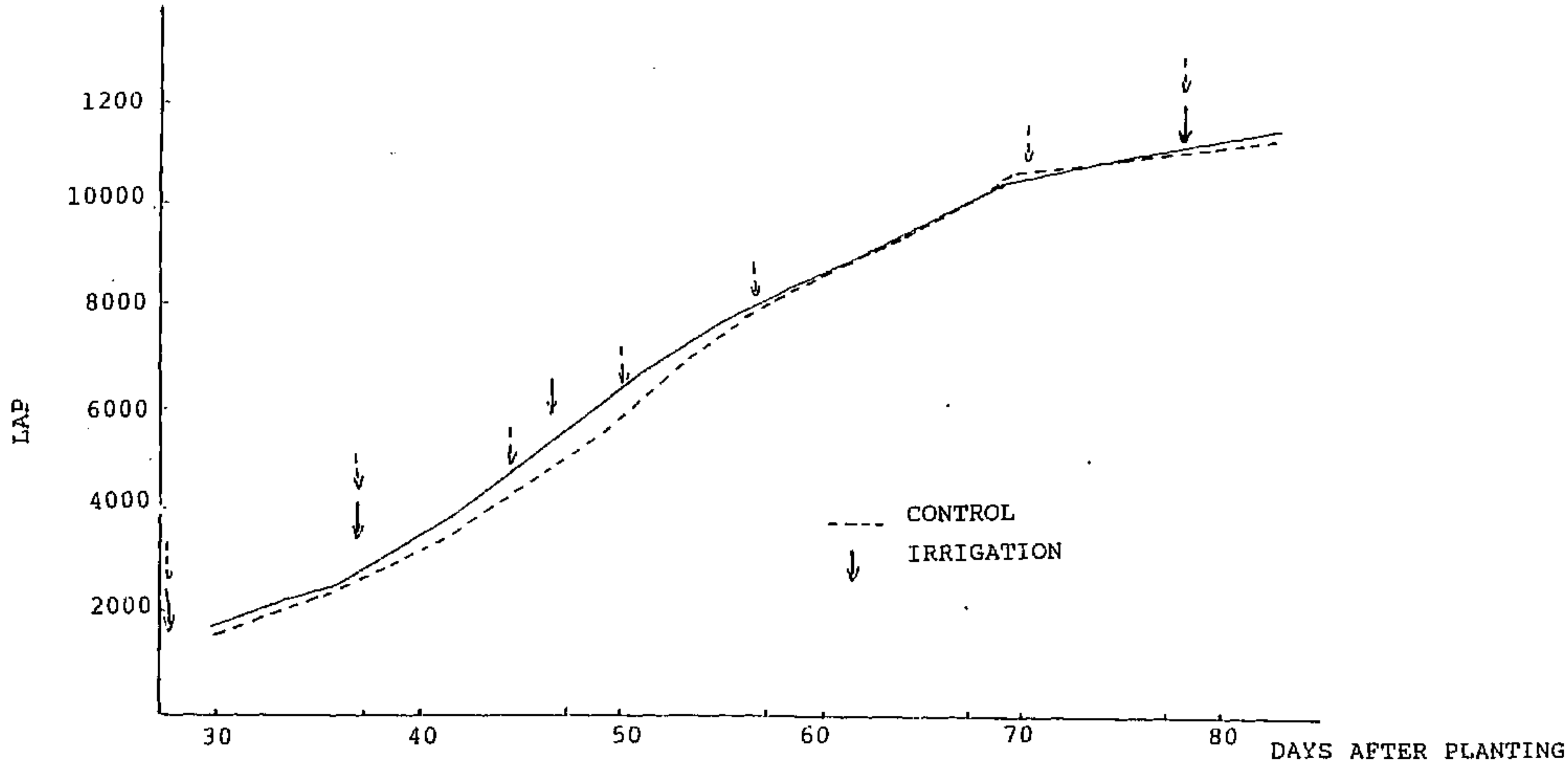


FIG.3.55 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT D6c (1986-1987 SEASON)

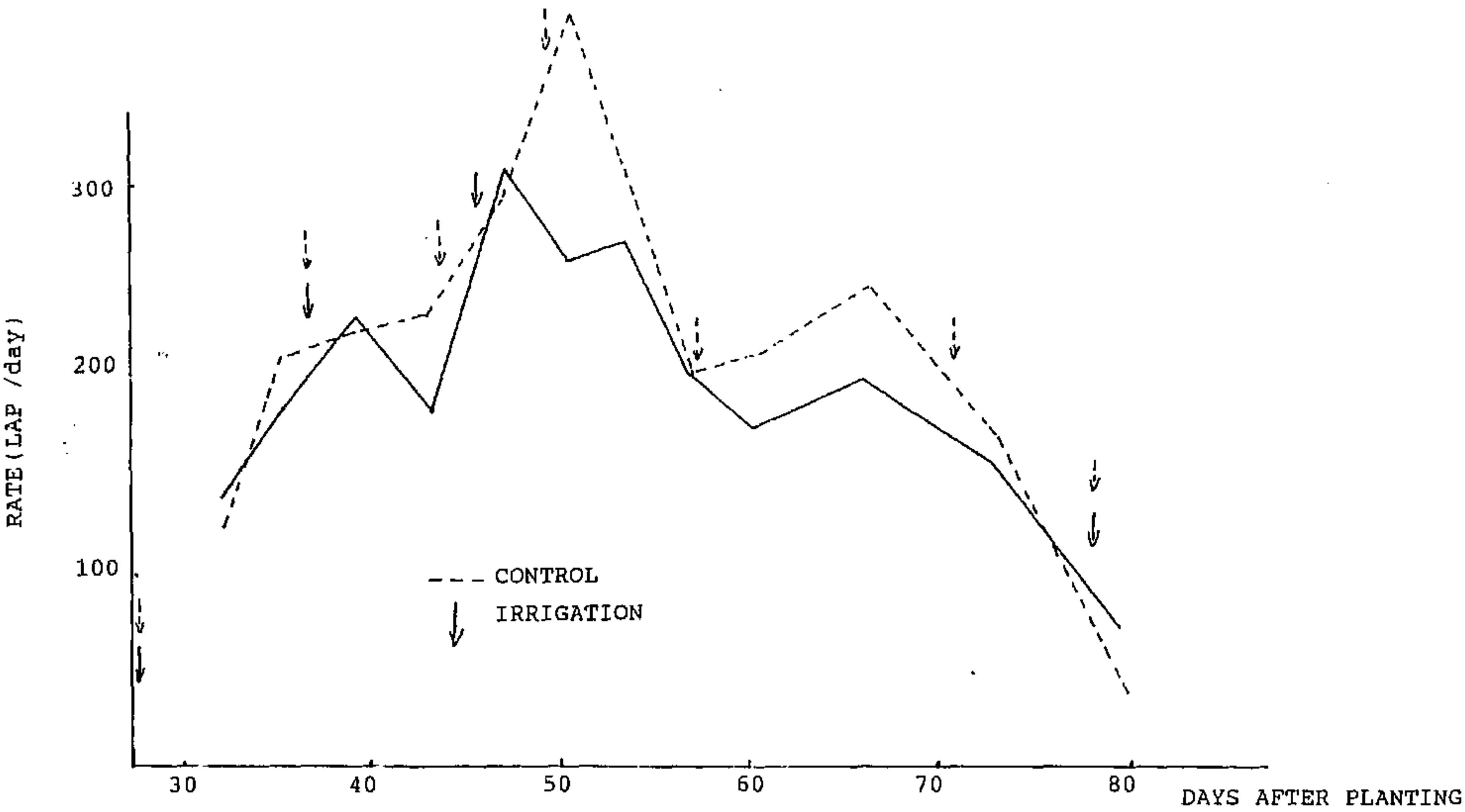


FIG.3.56 LEAF EXPANSION RATE OF MAIZE ON PLOT D6c (1986-1987 SEASON)

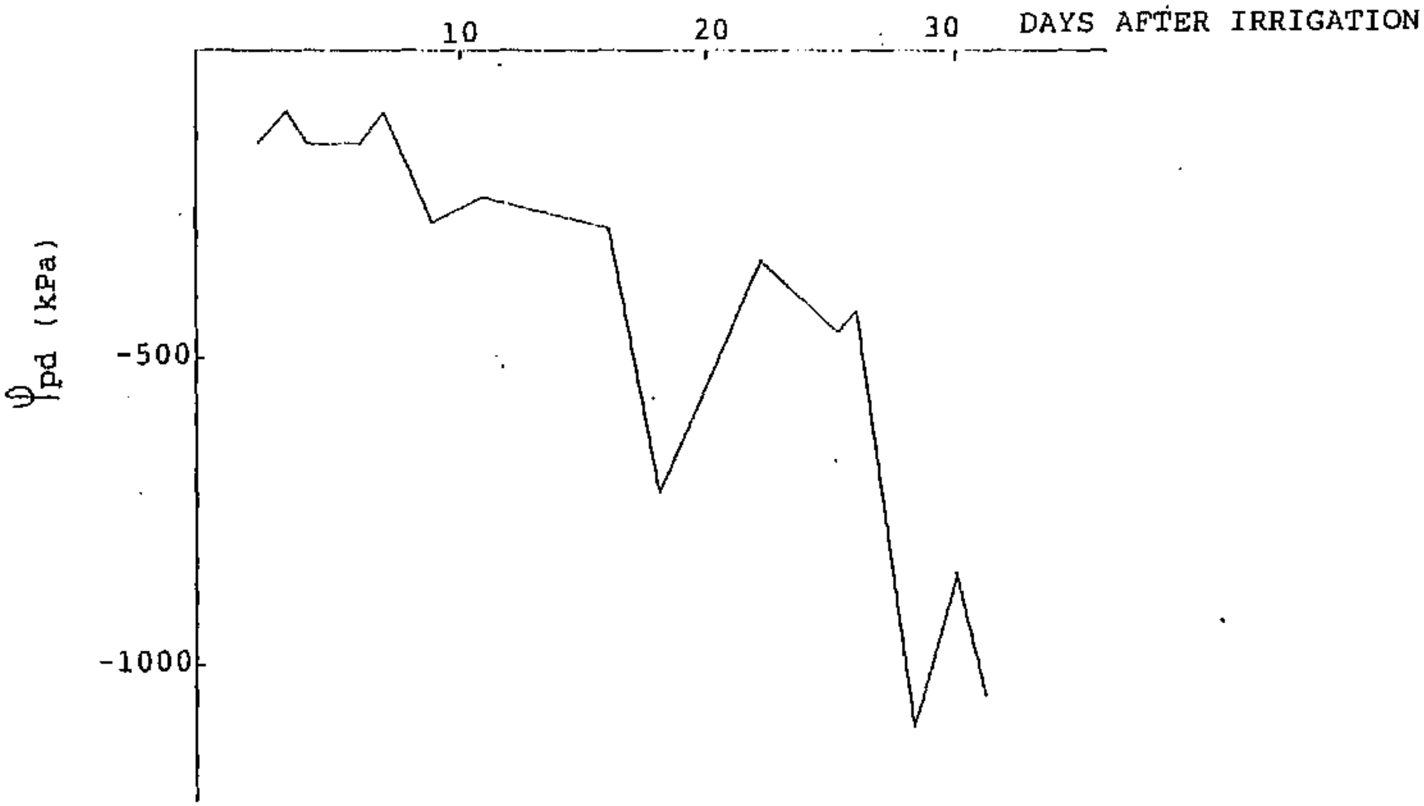


FIG.3.57 PRE-DAWN LEAF POTENTIAL PATTERN OF MAIZE ON PLOT D6c (1986-1987 SEASON)

after the start of the drying cycle. The leaf expansion rate could, therefore, not be used to indicate FMS. The drop of the rate at the end of the growing season was the result of the termination of the vegetative growth stage and was also found on the control plot and on the a, b and c-plots (Figures 3.58 and 3.59). The PLWP pattern was very different to the patterns found during the previous drying cycles. Soon after the final irrigation, the values decreased quickly to -500kPa and were fluctuating between -400kPa and -500kPa until FMS was observed (Figure 3.60). These were normal values for nearly fully grown maize plants and these tendencies were also observed during the 1985-1986 season. Bennie (UOFS, personal communication) also found that mature maize plants do not reach the high PLWP values found in younger plants, even under optimal conditions. Similar PLWP patterns in which the values of mature maize plants dropped quickly to -300kPa were found by Boedt & Laker (1985). Lorens, Bennett & Loggale (1987) also found a seasonal decrease in LWP of maize. The PLWP plateau of unstressed wheat and durum wheat was also found to be higher earlier in the season (Sections 3.2.1 and 3.2.2). FMS was indicated when PLWP dropped sharply from -500kPa to -1100kPa on day 20 of the drying cycle (shortly before silking stage).

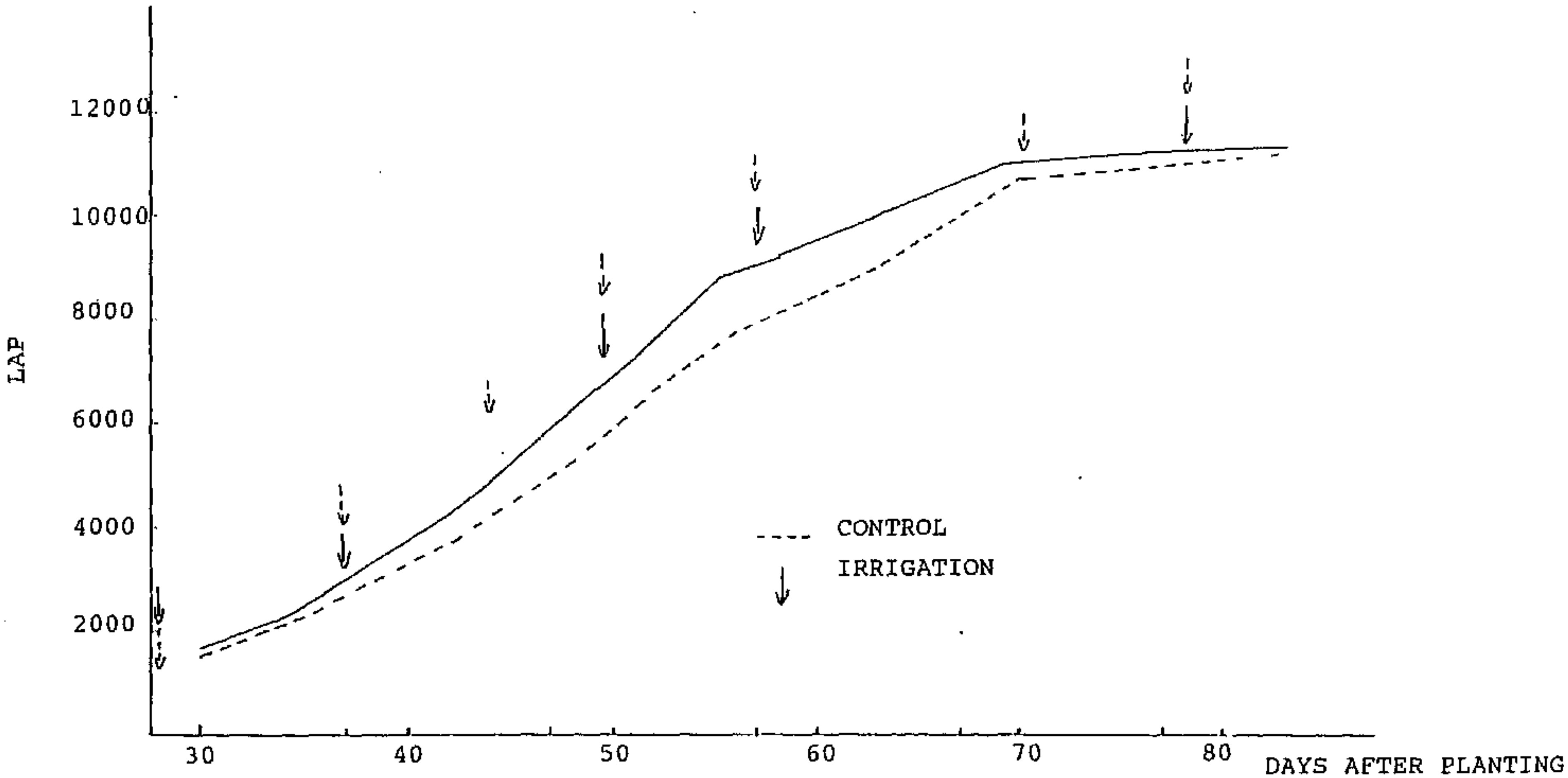


FIG.3.58 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT D6d (1986-1987 SEASON)

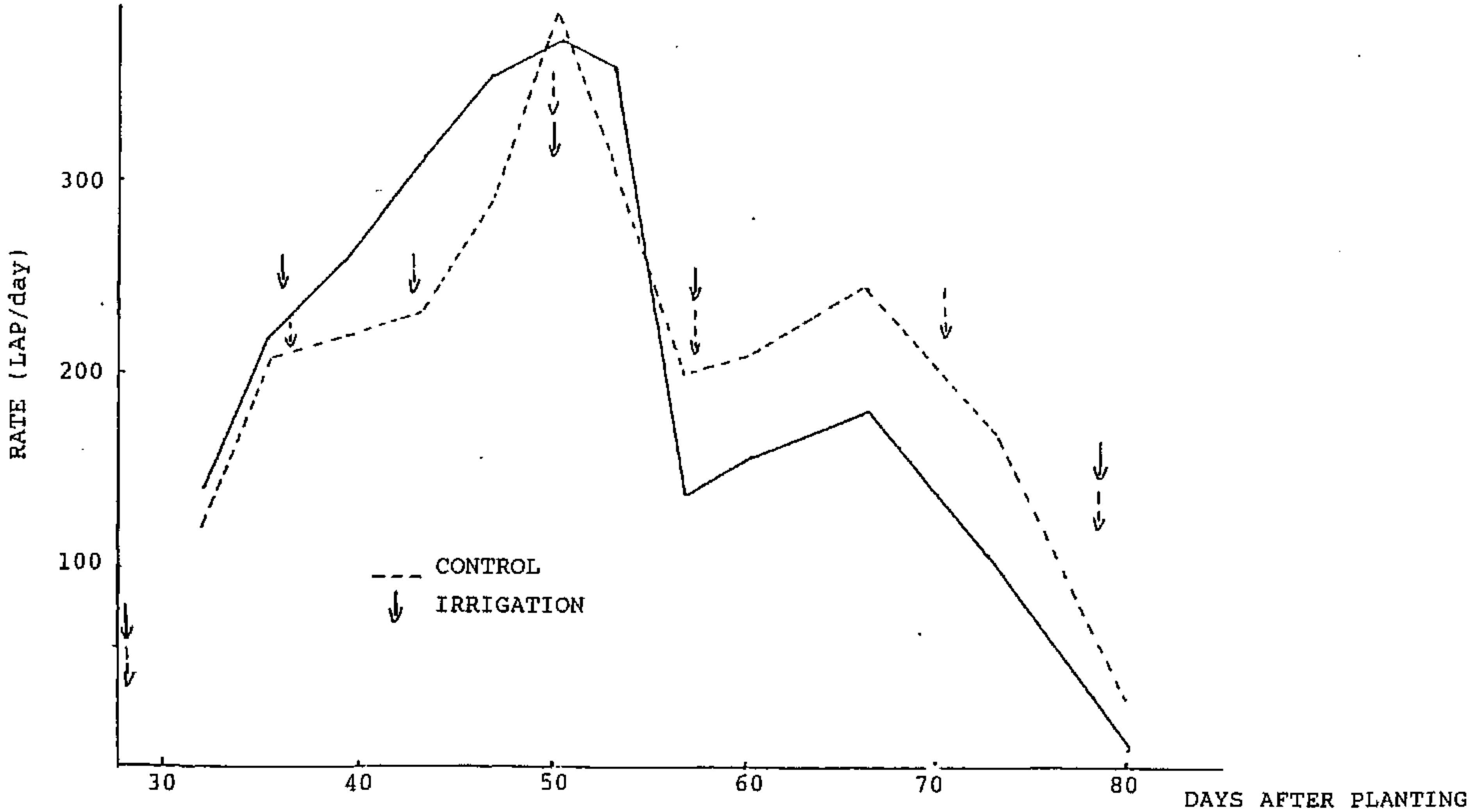


FIG.3.59 LEAF EXPANSION RATE OF MAIZE ON PLOT D6d (1986-1987 SEASON)

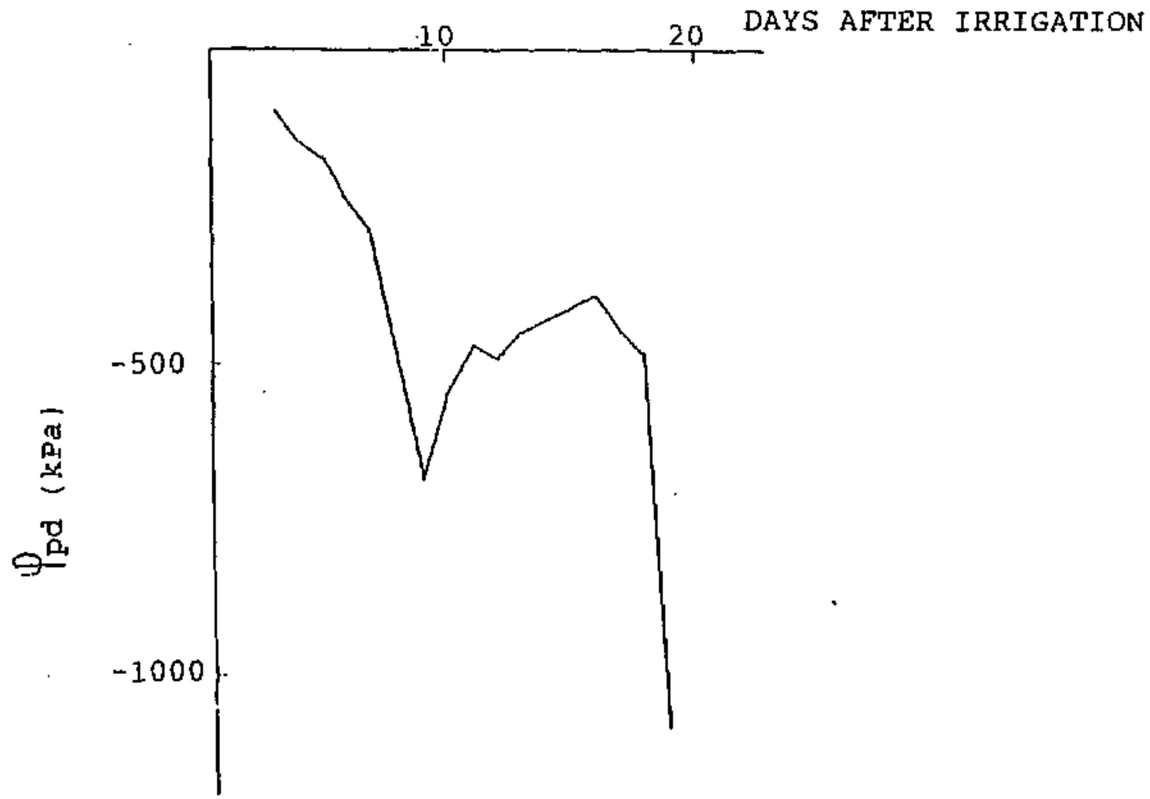


FIG.3.60 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE ON PLOT D6d (1986-1987 SEASON)

Similar results were found on plot D12d. The cumulative leaf expansion pattern was identical to the pattern found on control plot D12e throughout the drying cycle. The small difference in total leaf area at the end of the experiments was caused by a faster necrosis of the plant tissue on plot D12d (Appendices 3.1.34 and 3.1.35). Again leaf expansion measurements could not be used to indicate FMS because vegetative growth reached a natural termination before the onset of stress. The shape of the PLWP pattern was similar to that found on plot D6d, the values being even lower. FMS was observed when PLWP dropped from -600kPa to -1100kPa on the 19th day of the drying cycle, i.e. shortly before silking stage (Appendix 3.2.25).

TABLE 3.31 - Phenological growth stages at the start and end of the drying cycles, number of days to reach FMS and parameters used to identify FMS in maize at sites D6 and D12 (1986-1987 season)

Plot	Phenological stage start	end	days to FMS	parameters
D6a	4-leaf	12-leaf	30	LER and PLWP*
D6b	6-leaf	14-leaf	29	LER and PLWP*
D6c	8-leaf	16-leaf	28	PLWP
D6d	12-leaf	silking	20	PLWP
D12a	4-leaf	10-leaf	25	LER and PLWP*
D12b	6-leaf	14-leaf	28	LER and PLWP*
D12c	8-leaf	16-leaf	25	LER and PLWP
D12d	12-leaf	silking	19	PLWP

PLWP : Pre-dawn leaf water potential.
PLWP*: At -800kPa.
LER : Leaf expansion rate.

The phenological growth stages, the number of days to reach FMS and the parameters used to identify FMS in maize at sites D6 and D12 are summarized in Table 3.31.

3.2.3.2.2 Net carbon-dioxide exchange rate (NCER)

This study was conducted during the first half of December 1986 as a short period of intensive monitoring. Because Ceulemans and his co-workers could come to South Africa for a short period only at that time of the year and as the maize plants had to be at flowering stage for the experiments, the seeds were planted almost one month before the normal planting date.

Most of the measuring days were characterized by similar environmental conditions and the general trends could, therefore, be visualized by pooling daily values. On 15 December conditions were much more extreme, however (Figure 3.61). The radiation distribution and diurnal changes in PAR showed a uniform pattern and were similar on all measuring days with only a few scattered clouds slightly affecting it. Mean PAR was essentially the same on all measuring days, ranging from 1,83 to 1,94 mmol/sq.m.sec. Significant differences in leaf temperature (Tl) were measured between stressed and unstressed plants under the very dry and extreme

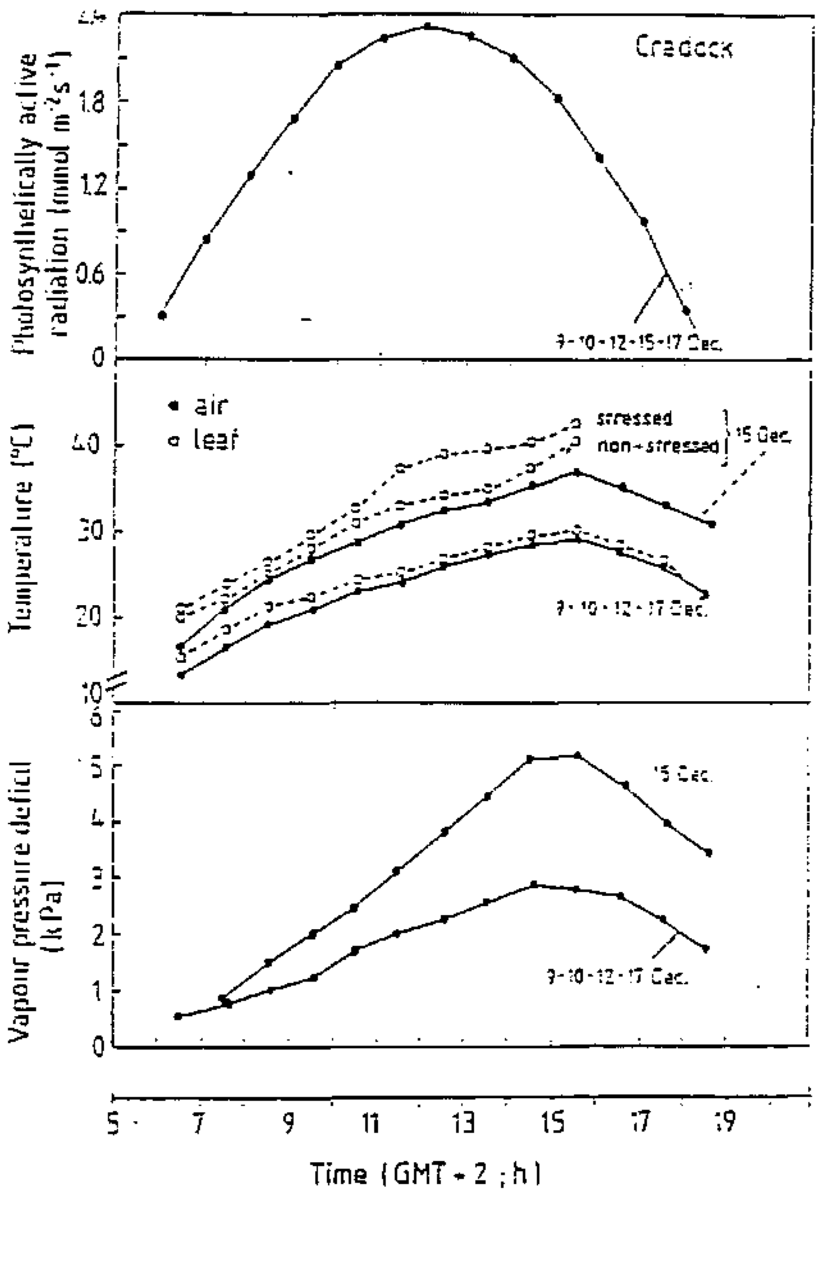


FIG. 3.61 Diurnal course of a number of independent environmental variables (PAR, air temperature and VSD) and leaf temperatures of stressed and unstressed maize plants on different sampling days (1986-1987 season). Mean values for similar days (9, 10, 12 and 17 December 1986) were compared with a much warmer and drier day (15 December 1986). From Ceulemans et al. (1988a).

conditions of 15 December (Figure 3.61).

NCER and LWP data of the five days were very similar and could, therefore, be pooled with one exception (Figure 3.62). The NCER data of 15 December were not included for calculation of the mean values but are presented seperately since it differed markedly from the others (dotted line in Figure 3.62). LWP val;ues of the stressed plants on 15 December were not significantly different from those measured on the other days and were, therefore. included in the average stressed curve. The stressed plants showed significantly lower NCER and LWP values compared to the unstressed plants, while extremely low NCER values were measured in the severely stressed plants (dotted line in Figure 3.62). The enlarged differences in NCER between unstressed and stressed plants were caused by a stimulation of NCER in the unstressed plants and an increased transpiration load on the stressed plants as a result of the high temperatures on that day. The diurnal changes in NCER generally reflected the LWP patterns, although a minor shift in the maxima (absolute values for LWP) around noon was observed. The variation in NCER was much less on stressed plants than on well-watered plants.

Soil water stress had a significant effect on NCER, which

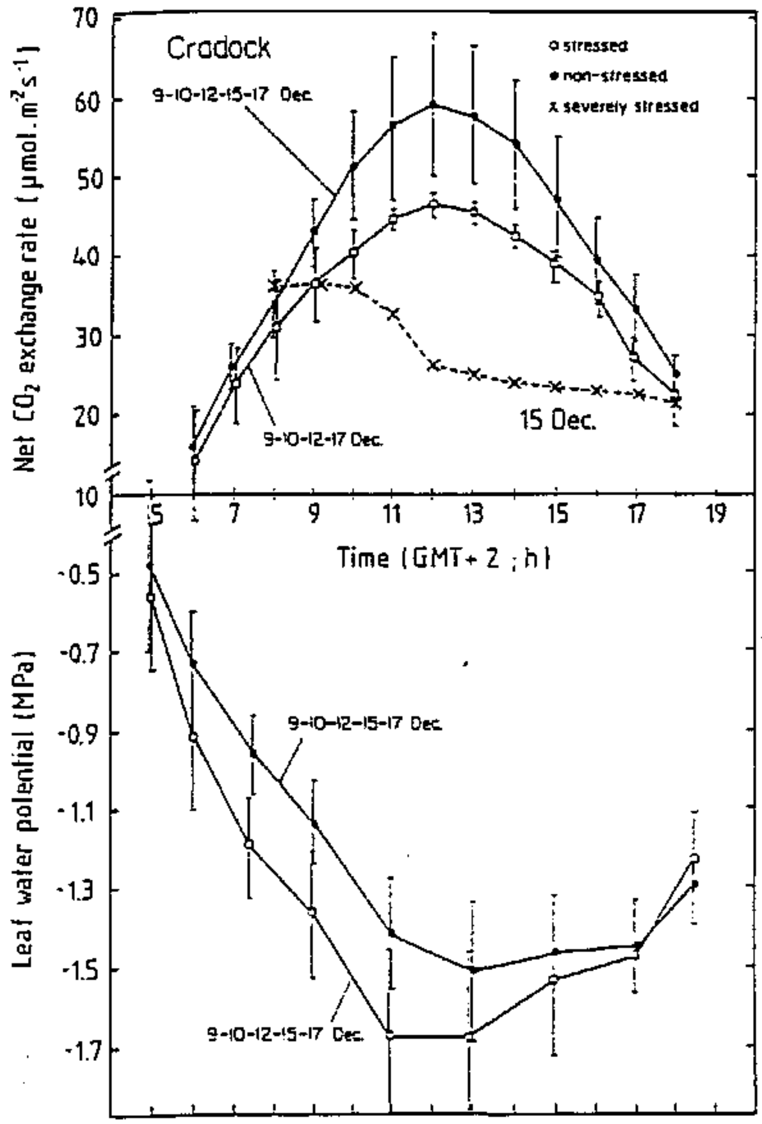


FIG. 3.62 Diurnal course of net carbon-dioxide exchange rate (NCER) and leaf water potential (LWP) of stressed, unstressed and severely stressed maize plants (1986-1987 season). For unstressed NCER and for all LWP data, mean values of five measuring days are shown. Measurements of 15 December 1986 were not included in the average NCER of the stressed treatment. Vertical bars represent standard deviation of the mean. From Ceulemans et al. (1988a).

decreased as soon as 20 to 30% of PAWC was extracted. Average day-time NCER values decreased from about 48 mmol/sq.m.sec. for well-watered plants to about 25 mmol/sq.m.sec. for severely stressed plants (Figure 3.63). Pre-dawn LWP showed no clear response to the amount of PAWC extracted from the soil profile but average day-time LWP was fairly constant until more than 60% of PAWC was extracted after which it decreased with increasing percentage of PAWC extracted (Figure 3.63). The average day-time NCER and LWP values were mean values of all NCER and LWP readings between 0800h and 1800h. It was assumed that there was no light limitation for stomatal opening during that period.

When maximal NCER values (at noon) are plotted against soil water content, the significant declining response of NCER to increasing percentages of PAWC extracted becomes even more pronounced, especially when Ta on the days of measurement was about the same (Figure 3.64). The maximal NCER values measured at noon on 15 December diverged more from the maximal values found on the other days than the average day-time NCER did for both stressed and well-watered plants. NCER seemed to respond sharply to environmental conditions in the wet soil range and much less so in the lower PAWC range. This was also found with stomatal conductance (Section 3.2.3.1.3).

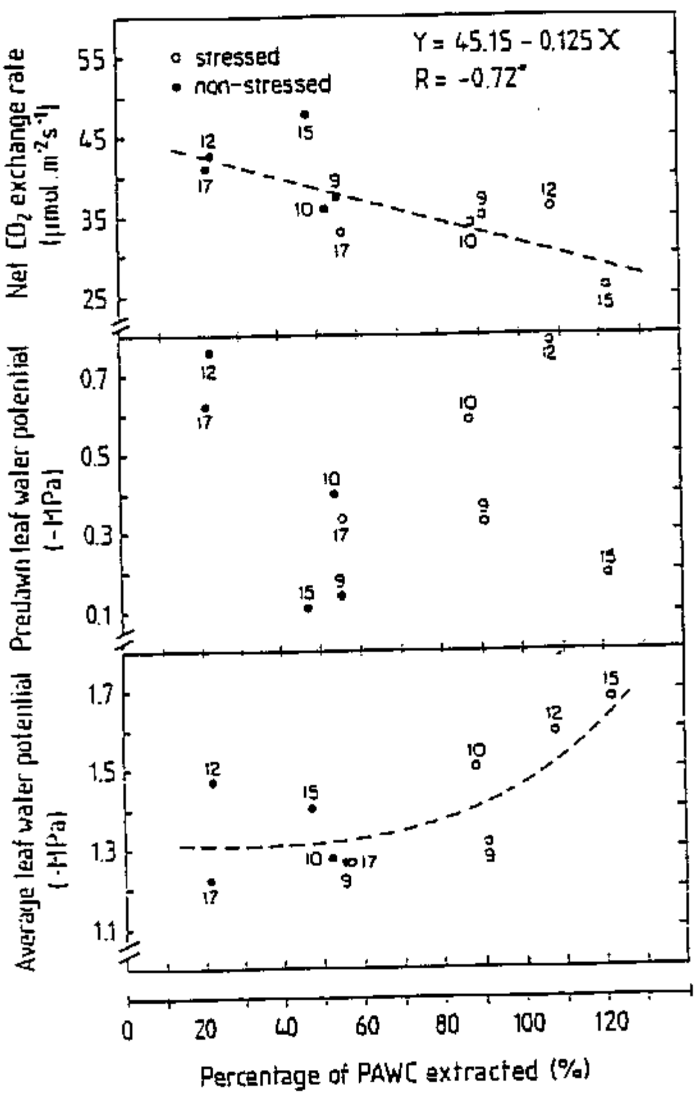


FIG. 3.63 NCER (mean value between 0800 and 1800h), pre-dawn leaf water potential (at 0500h) and mean daytime LWP (mean value between 0800 and 1800h) of stressed and unstressed maize plants as a function of soil water content (1986-1987 season). Soil water content is expressed as a percentage of PAWC extracted. Labels at each data point represent dates in December 1986. The regression is significant at 5% level (*). From Ceulemans et al. (1988a).

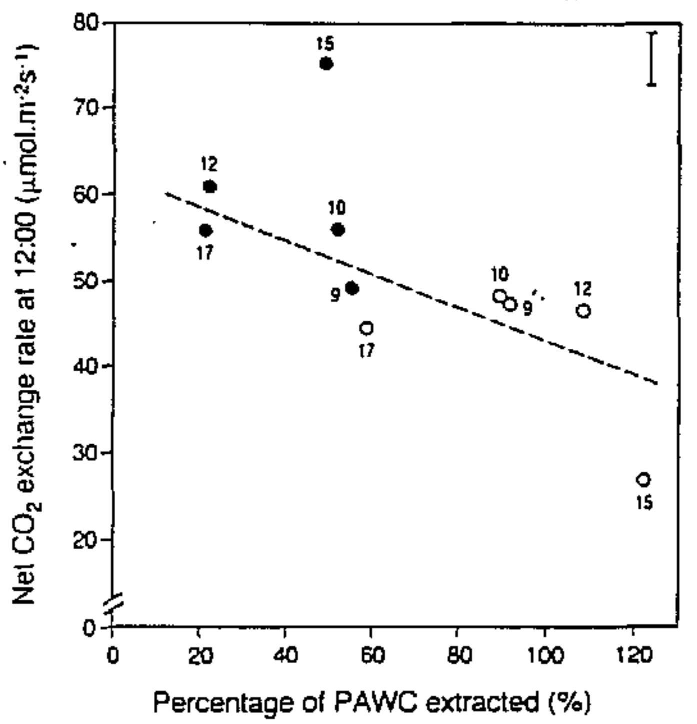


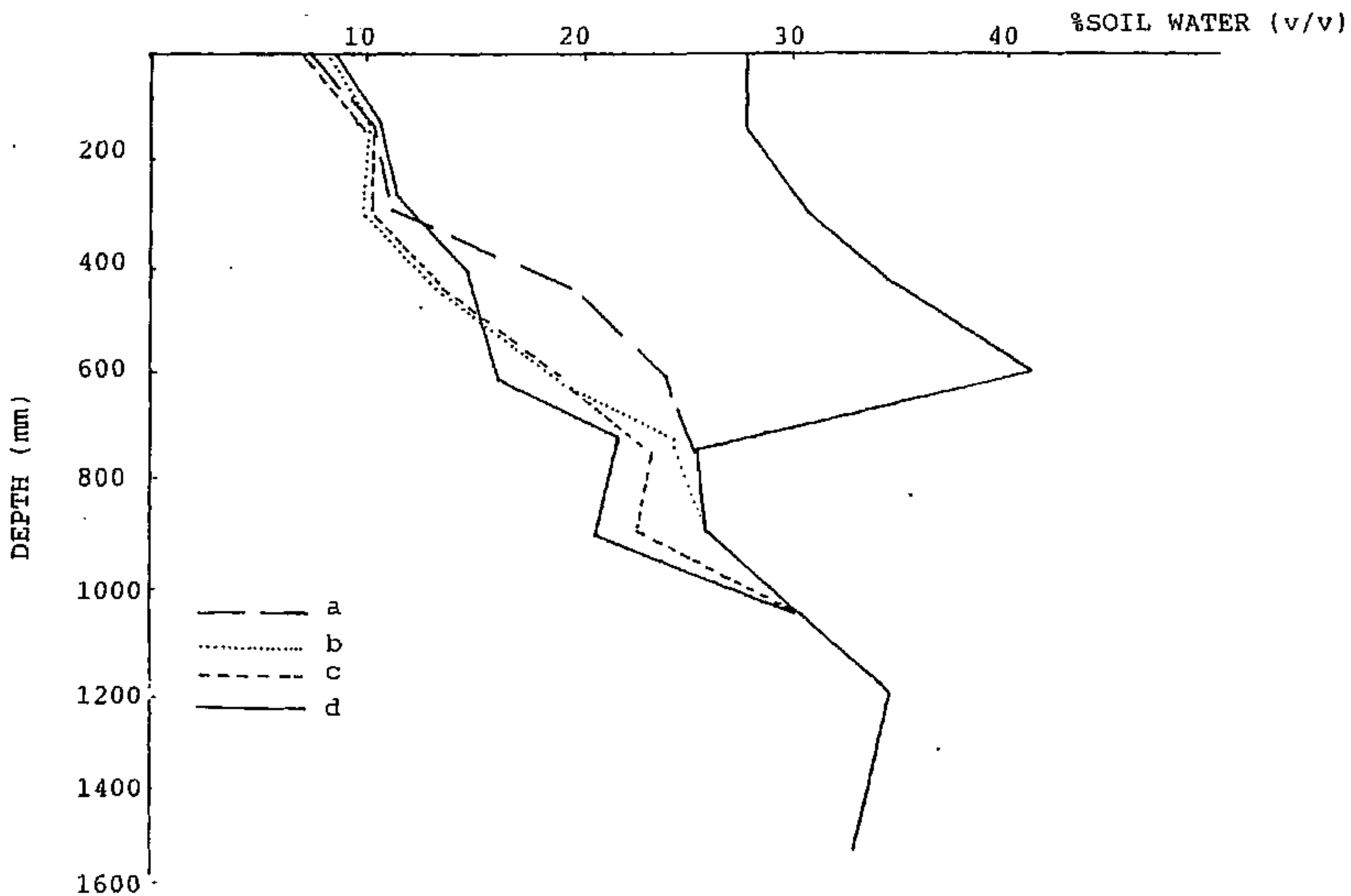
FIG. 3.64 Maximal NCER (at noon) of stressed and unstressed maize plants as a function of soil water content, expressed as a percentage of PAWC extracted (1986-1987 season). Labels at each data point represent dates in December 1986. Each data point is the mean of ten replications and an overall estimation of the standard deviation on the means is given (vertical bar). Linear regression is significant at the 1% level. From Ceulemans et al. (1988a).

A comprehensive discussion of this study is given by Ceulemans et al. (1988a).

3.2.3.2.3 PAWC values and soil water extraction patterns

The soil water extraction patterns for the different growth stages at site D6 are illustrated in Figure 3.65. The basic shape of the patterns was a fan shape, similar to those found for wheat and durum wheat at this site. The convergence point, marking the lower boundary of the effective root zone, was at a depth of 750mm at stage a. The compacted B horizon impeded root penetration and development in soil layers deeper in the profile. This theory was confirmed by the soil water extraction pattern of plot D12a where the convergence point was already at a depth of 1200mm at that stage as there was no compacted horizon to prevent root penetration (Figure 3.66). The evolution of the extraction patterns from stage a (12-leaf stage) to stage d (silking stage) consisted mainly in a downward movement of the convergence point from a depth of 750mm to a depth of 1050mm, although the biggest increase of soil water extraction was found between 300mm and 750mm depth. The quantities of soil water extred at different soil depths and the PAWC values for each growth stage are listed in Table 3.32. The results confirmed the suspicions that hail damage

FIG.3.65 SOIL WATER EXTRACTION PATTERNS OF MAIZE AT FIRST MATERIAL STRESS AT DIFFERENT GROWTH STAGES AT SITE D6 (1986-1987 SEASON)



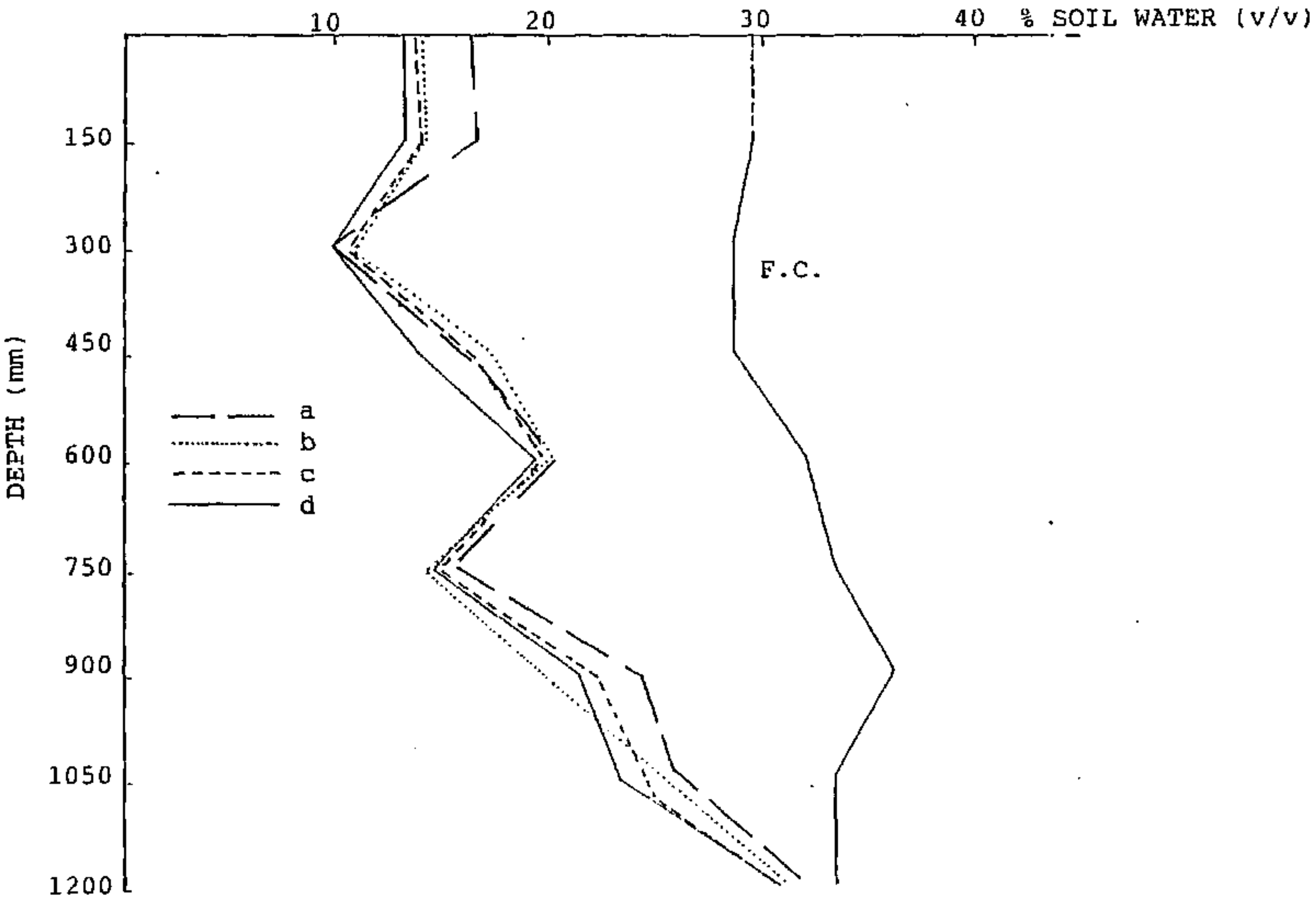
during the previous season had delayed the evolution of the PAWC values. The PAWC at stage a (12-leaf) of 124mm was identical to that found during the previous season (121mm). At that stage the plants were not damaged by hail during the 1985 season. The PAWC at stages b (14-leaf) and c (16-leaf), the latter identical to stage b during 1985-1986 season, was higher than the PAWC found during the previous season when hail had damaged the plants very severely (Compare Tables 3.25 and 3.32). The PAWC for stage d (silking stage) was identical to that found at flowering during the first season. The maximum PAWC value of 159mm was already reached at stage c (16-leaf stage).

TABLE 3.32 - Quantities of soil water extracted by maize at different soil depths and PAWC values for each growth stage at site D6 (summer 1986-1987)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	d
0- 100	18,0	17,0	16,8	16,3
100- 200	19,8	19,3	18,3	17,3
200- 300	22,5	23,3	22,0	19,3
300- 400	18,5	24,8	24,3	22,5
400- 500	18,5	27,0	27,0	26,0
500- 600	21,3	28,8	28,5	29,5
600- 700	5,0	12,5	12,0	12,5
700- 800		3,0	4,3	4,5
800- 900			5,5	8,8
900-1000			1,2	2,5
1000-1100				
PAWC	123,6	155,7	159,9	159,2

The soil water extraction patterns for site D12 are illustrated in Figure 3.66. Again the same basic fan shape was found, supporting the theory that the basic shape of the extraction pattern is mainly based on the soil profile characteristics. The crop itself only determines the depth of the convergence point and the width of the fan, depending on the extent of the root system. The evolution of the soil water extraction patterns consisted in the downward movement of the convergence point from a depth of 1200mm at stage a to a depth of 1300mm at stage d and in the widening of the gap between field capacity and first stress lines. The quantities of soil water extracted at different soil depths and the PAWC values for each growth stage are listed in Table 3.33. The PAWC values were higher than those found during the 1985-1986 summer experiments, especially at the younger growth stages (Compare Tables 3.26 and 3.33). The PAWC value at stage b (149mm) was very close to the value found at flowering stage (154mm). Stage c (16-leaf stage) for the 1986-1987 season, which corresponds with stage b for the 1985-1986 season, gave a PAWC of 153mm compared to 120mm for the same growth stage during the previous season. These results proved again that hail damage had delayed the evolution of the PAWC values during the vegetative growth stages during the previous season. The evolution of PAWC of maize at

FIG.3.66 SOIL WATER EXTRACTION PATTERNS OF MAIZE AT FIRST MATERIAL STRESS AT DIFFERENT GROWTH STAGES AT SITE D12 (1986-1987 SEASON)



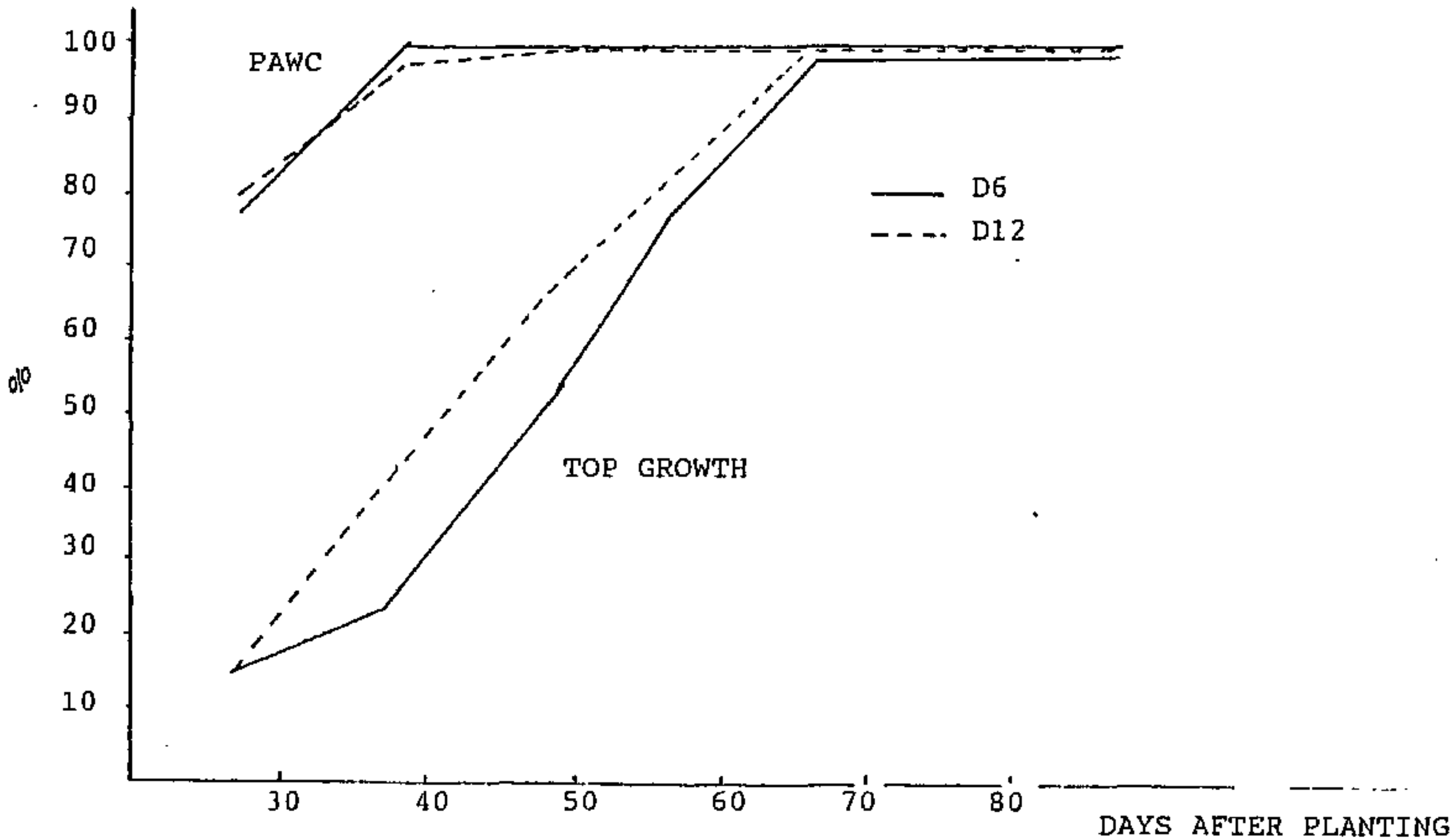


FIG.3.67 RELATIVE PAWC AND RELATIVE TOP GROWTH OF MAIZE AT SITES D6 AND D12 (1986-1987 SEASON)

different growth stages and the top growth at sites D6 and D12 is illustrated in Figure 3.67.

TABLE 3.33 - Quantities of soil water extracted by maize at different soil depths and PAWC values for each growth stage at site D12 (summer 1986-1987)

Depth (mm)	Soil water extracted (mm)			
	a	b	c	d
0- 100	10,5	15,5	15,5	15,3
100- 200	14,5	16,3	16,3	16,0
200- 300	13,3	16,0	17,0	17,5
300- 400	13,0	13,8	14,0	15,0
400- 500	10,5	11,5	12,0	13,0
500- 600	10,0	10,0	11,0	11,8
600- 700	14,0	14,8	15,3	15,8
700- 800	14,0	16,5	16,0	16,5
800- 900	11,0	14,8	14,0	13,8
900-1000	8,8	11,0	10,5	10,8
1000-1100	3,0	6,0	7,0	6,5
1100-1200	1,0	2,5	4,0	1,5
1200-1300				
PAWC	123,6	148,7	152,6	153,5

3.2.3.2.4 Effects of water stress on vegetative growth and yield

The final leaf area parameter (LAP) and the calculated leaf area index (LAI) of maize for each plot are listed in Table 3.34. The plants at site D6 were less sensitive to soil water stress at every growth stage than the plants at site D12. This was also found with wheat and durum wheat. The effects of soil water stress were less severe at site D6 and this was explained by the high amount of available water in the upper part of the profile due to the restricting layer at 700mm depth. Statistical analysis (randomized complete block design) of the data in Table 3.34 indicated that there were no significant differences between the treatment means. However, the mean LAP and LAI clearly illustrate that the effect of soil water stress on leaf expansion decreases as the plants are closer to maturity and that leaf expansion does not completely recover after a period of stress. Similar results were also found by Human & De Bruyn (1988).

TABLE 3.34 - Leaf area parameter (LAP) and leaf area index (LAI) of maize at the end of the experiments at sites D6 and D12 (summer 1986-1987)

Plot	LAP			LAI		
	D6	D12	ave.	D6	D12	ave.
a	10700	9700	10200	3,3	3,0	3,2
b	10500	10500	10500	3,3	3,3	3,3
c	11600	10900	11250	3,6	3,4	3,5
d	11500	11100	11300	3,6	3,5	3,6
e	11300	11700	11500	3,5	3,7	3,6
lsd (p=0,05)			ns			ns

During the experiments an early pollination was observed on the stressed plots, before the silk was ready to receive the pollen. In the experimental area there were enough well-watered plots to ensure adequate pollen at the correct time. In large, dry fields such early pollination can be disastrous. It is therefore important that enough water is available for the plants some time before flowering stage in order to prevent poor pollination and a resulting decrease in grain yield. Unfortunately, a hailstorm destroyed most of the leaves when the plants were at the grain filling stage, resulting in low grain yields (Table 3.35). Statistical analysis indicated that there were no significant differences between the treatment means. This was also found during the 1985-1986 season.

TABLE 3.35 - Grain yield of maize at a moisture content of 12.5% harvested at sites D6 and D12 (summer 1986-1987)

Plot	Grain yield (ton/ha)		
	D6	D12	average
a	5,65	6,18	5,92
b	5,89	6,06	5,98
c	6,67	7,27	6,97
d	4,73	6,40	5,57
e	5,52	7,12	6,32
lsd (p=0,05)			ns

3.2.3.3 Summer 1987-1988

The aim of the experiment, conducted at site ISO-B, was to study the effect of modererate and severe soil water stress on leaf expansion and stem elongation. Stem elongation consisted of measuring the total height of the plants and the distances between successive leaves (See

Chapter 2). The nature of the experiment was to impose moderate and severe water stress at three different growth stages. FMS was detected by regular PLWP and leaf expansion measurements. A PAWC value of 110mm was found for treatment 100-4 for which FMS was detected at the 11-leaf stage. PAWC values for treatments 100-10 (FMS at flowering stage) and 100-15 (FMS at grain filling stage) were between 145mm and 150mm. Eight treatments, each with four replications, were as follows:

treatment control: refilled to field capacity when 30% to 50% of PAWC was extracted.

treatment 100-4: drying cycle started at four leaf stage and 100% of PAWC extracted.

treatment 125-4: drying cycle started at four leaf stage and 125% of PAWC extracted.

treatment 100-10: drying cycle started at ten leaf stage and 100% of PAWC extracted.

treatment 125-10: drying cycle started at ten leaf stage and 125% of PAWC extracted.

treatment 100-15: drying cycle started at fifteen leaf stage and 100% of PAWC extracted.

treatment 125-15: drying cycle started at fifteen leaf stage and 125% of PAWC extracted.

treatment 50-75: deficit irrigation; refilled with 50% of PAWC when 75% of PAWC was extracted.

3.2.3.3.1 Effect of water stress on leaf expansion

The leaf area index (LAI) of maize for each treatment was calculated from the total length of the leaves of a plant (See Chapter 2) and is listed in Table 3.36. Statistical analysis, using the method described by Steel & Torrie (1980) for a completely randomized design, indicated that there were statistically significant differences between the treatments. The differences between LAI means are given in Table 3.37. The results show that severe soil water stress during the vegetative growth stages (treatments 125-4 and 125-10) reduced the leaf area significantly. Rewatering did not result in an increased leaf expansion. Treatments 100-15 and 125-15 did not result in significantly smaller leaf areas due to the fact that at the time of water stress these plants were reaching maturity and vegetative growth was terminated.

TABLE 3.36 - Leaf area index (LAI) of maize at the end of the growing season for each irrigation treatment at site ISO-B (summer 1987-1988)

Treatment	Leaf area index				
	rep.1	rep.2	rep.3	rep.4	aver.
control	4,0	3,9	4,3	4,3	4,1
100-4	4,2	3,6	3,9	3,6	3,8
125-4	3,8	3,7	3,8	3,1	3,6
100-10	3,8	4,5	3,0	4,1	3,9
125-10	3,2	3,5	3,3	3,3	3,3
100-15	3,5	3,9	3,1	4,1	3,7
125-15	4,5	3,8	3,9	4,1	4,1
50-75	3,7	4,5	3,6	3,5	3,8
				lsd (p=0,05)	0,5

TABLE 3.37 - Differences in leaf area index of maize between different irrigation treatments at site ISO-B (summer 1987-1988)

	Differences						
treatments	125-10	125-4	100-15	100-4	50-75	100-10	125-15
control	0,8*	0,5*	0,4	0,3	0,3	0,2	0,0
125-15	0,8*	0,5*	0,4	0,3	0,3	0,2	
100-10	0,6*	0,3	0,2	0,1	0,1		
50-75	0,5*	0,2	0,1	0,0			
100-4	0,5*	0,2	0,1				
100-15	0,4	0,1					
125-4	0,3						

* = significant at 5% level.

3.2.3.3.2 Effect of water stress on stem elongation

The total height of the maize plants was measured at the end of the growing season and the results are listed in Table 3.38. The data were statistically analyzed according to the method of Steel & Torrie (1980) for a complete randomized design. The analysis indicated that there were highly significant differences between the treatments (Table 3.39). This means that stem elongation was more sensitive to water stress than leaf expansion. Plants which had experienced severe soil water stress during the early vegetative stages (treatments 125-4 and 125-10) were significantly shorter than those which had experienced moderate water stress during early vegetative growth stages (treatment 100-4) and those which had experienced water stress (severe and moderate) during the late vegetative stages (treatments 100-15 and 125-15). Severe soil water stress during the early vegetative stages (treatment 125-4) resulted in significantly shorter plants than moderate water stress during a later vegetative stage. Moderate water stress did not affect the stem elongation significantly, except when it was applied during mid-vegetative growth stages (treatment 100-10). Severe and moderate water stress during the late vegetative stages (treatments 100-15 and 125-15) did not affect the stem elongation as vegetative growth was terminated at the time of water stress.

TABLE 3.38 - Final height of maize plants for different irrigation treatments at site ISO-B (summer 1987-1988)

Treatment	Height (cm)				
	rep.1	rep.2	rep.3	rep.4	aver.
control	245	250	235	220	238
100-4	250	220	220	185	219
125-4	160	190	197	160	177
100-10	210	225	190	220	211
125-10	195	210	175	195	194
100-15	225	245	210	245	231
125-15	245	250	240	225	240
50-75	220	245	215	245	231
				lsd (p=0,05)	23
				(p=0,01)	31

TABLE 3.39 - Differences in final height of maize plants for different irrigation treatments at site ISO-B (summer 1987-1988)

Differences (cm)

treatments	125-4	125-10	100-10	100-4	100-15	50-75	control
125-15	63**	46**	29*	21	9	9	2
control	61**	44**	27*	19	7	7	
50-75	54**	37**	20	12	0		
100-15	54**	37**	20	12			
100-4	42**	25*	8				
100-10	34**	17					
125-10	17						

** = significant at 1% level.
* = significant at 5% level.

Compared to leaf expansion, stem elongation was more sensitive to water stress. Stem elongation indicated differences between severe and moderate water stress and was also able to identify moderate water stress during mid vegetative growth stages (treatment 100-10) where leaf expansion could not.

The final height of a maize plant indicates whether water stress has been experienced or not when compared with the height of well-watered control plants. It does however not indicate when water stress was experienced. To assess when water stress was experienced it is necessary to measure the distance on the stem between successive leaves. The results of those measurements are given in Table 3.40. The number in the "leaf" column indicates the part of the stem between the leaf as indicated by the number and the one above it (f.i. the distance between leaf 3 and leaf 4 is indicated by the number 3). The position of leaf 1 was taken as reference level zero. The * sign indicates where the length is significantly smaller than that measured on the control plants and where water stress was experienced.

TABLE 3.40 - Length between successive leaves of maize for different irrigation treatments at site ISO-B (summer 1987-1988)

Leaf	Length (mm)							
	contr.	100-4	125-4	100-10	125-10	100-15	125-15	50-75
1	16	20	18	18	18	18	24	20
2	16	20	20	18	23	20	16	20
3	16	16	15	14	18	21	26	20
4	30	41	39	36	30	35	33	34
5	43	35	38	34	39	44	45	40
6	51	50	48	44	53	58	50	53
7	56	49	59	56	51	57	60	58
8	76	79	66	64	68	95	81	65
9	90	91	78	90	90	133	99	104
10	120	104*	81*	119	122	155	137	118
11	126	110*	85*	131	136	144	146	133
12	140	128*	85*	143	128	159	149	145
13	139	140	85*	131	136	155	155	141
14	134	151	95*	131	149	163	160	161
15	154	155	109*	135*	124*	158	158	168
16	161	150	128*	130*	125*	145	155	159
17	163	145	115*	116*	105*	140	143	145
18	150	139	123*	110*	91*	140	148	141
19	133	120	114*	99*	79*	120	130	110
20	125	118	106*	96*	66*	110	113	110
21	104	95	90	88	58*	105	105	91
22	111	92	87	97	52*	105	97	98
23	85	90	90	93	48*	85	85	85
24	45	40	45	45	55	50	45	45

* = statistically significant reductions due to water stress.

3.3 DISCUSSION

3.3.1 Wheat

Both stem elongation rate and PLWP patterns clearly indicated the onset of first material stress during young growth stages (until the flag leaf was completely developed, stage 9 according to Large, 1954). In order to identify FMS using PLWP or stem elongation rates, it is necessary to study a long-term pattern starting as soon as possible after irrigation with daily measurements until water stress has clearly set in. Single SER or PLWP values cannot be used as indications of FMS since both parameters seem to be susceptible to climatic fluctuations and atmospheric induced water stress is unavoidable. The use of a well-watered control plot is, therefore, recommended.

It became clear that during early growthh stages (i.e. until stage 7 according to Large, 1954) wheat plants are more sensitive to reductions in PLWP than during later growth stages. During these early growth stages FMS was clearly identified when PLWP decreased to about -800kPa. During later stages FMS is indicated only by PLWP values of clearly less than -1000kPa, as was also found by Boedt & Laker (1985). Similar results for early growth stages were also found for durum wheat and maize. During later growth stages i.e. when ear was in boot or later (stage 10 according to Large, 1954) SER failed to indicate FMS as the plants were almost fully grown. PLWP patterns clearly indicated FMS in mature plants when values dropped below -1000kPa.

During the young growth stages (vegetative growth stages) stem elongation rates dropped significantly relative to the non-stressed plots when water stress was induced. These reductions in stem elongation were not found when water stress occurred during the reproductive growth stages i.e. from stage 10 (Large, 1954) onwards. Similar reductions in leaf area and stem elongation of wheat plants under water stress conditions during vegetative growth stages were also found by Aspinall et al. (1964), Begg & Turner (1976), Oosterhuis & Cartwright (1983) and Human & De Bruyn (1988). Reductions in stem elongation during early vegetative growth stages is mainly caused by reduction in turgor, resulting in a lower cell expansion (Hsiao, 1973). Hoogenboom et al. (1987) observed significant reductions in stem elongation of soybean plants when water stress was induced during vegetative growth stages. Water stress during later stages of reproductive growth did not affect final shoot size of soybean plants (Hoogenboom et al., 1987). This confirms the observations of Ramseur, Wallace & Quisenberry (1985) who stated that vegetative growth ceases after seed formation has begun. Huck et al. (1983) also reported that the forming of vegetative nodes in soybean ceases with the onset of reproductive development.

Irrigation at the end of the drying cycles resulted in increased stem elongation rates which sometimes exceeded those of the non-stressed plants if soil water stress had been induced during early vegetative growth stages i.e. at the end of tillering stage. This shows that plants that have been exposed to water stress during the early vegetative growth stages show optimal growth after rewatering that may exceed that of non-stressed plants and, thus, stressed plants and non-stressed plants end up comparable in size at the end of the growing season. In other words, water stress during early vegetative stages had no evident long-term effects on the final height of the wheat plants. When soil water stress occurred during later vegetative stages (stem extension stage) rewatering did not result in stem elongation rates exceeding those of the control plots and plants were significantly shorter than the non-stressed plants at the end of the growing season (Table 3.8). Similar increases in stem elongation upon irrigation of water stressed soybean plants were observed by Hoogenboom et al. (1987).

Typical for almost all PLWP patterns was the fluctuating phase observed at the end of the drying cycles. This phase was characterized by a more or less rhythmic oscillation between low (under -1000kPa) and relatively high values (-500kPa) with decreasing low values. This pattern reflects the ability of the plant for temporary recovery. Similar patterns were found during drying cycles with maize by Boedt & Laker (1985). From these patterns they derived a stress curve by connecting the lower points (temporary stress) of the oscillations. According to Boedt & Laker (1985) this type of pattern illustrates the "specific soil - plant - atmosphere - continuum (SPAC) situation under which the plant cannot recover overnight but can recover over a longer period."

One of the mechanisms that may be involved is secondary root growth which reaches soil layers with a higher water content. This confirms the observations of Hoogenboom et al. (1987). They found a major increase in root length, especially in the deeper soil layers, when water stress occurred. This increased growth is caused by an increase in transport of photosynthetic assimilates to the roots when plants experience water stress. This mechanism does not seem to work when water stress is experienced during later reproductive growth stages (Hoogenboom et al., 1987). The fact that PLWP patterns of wheat stressed at flowering stage (stage f 1985 winter season) did not show these oscillations confirms this theory. Lang & Thorpe (1986) also reported that water potential differences within the plant affected the partitioning of the assimilates and found that regions with the highest potentials attracted most of the assimilates. Another confirmation of this theory is the discrepancy between relative top growth and relative PAWC during vegetative stages. The relatively high PAWC values of wheat found during young growth stages (1985 winter season) indicated the effect of soil water stress on the relationship between root growth and top growth found by various researchers (Erickson, 1976; Botha et al., 1983; Muller, 1988). Although the maximum PAWC values were not reached early in the growing season during the 1986 winter experiments, relative PAWC values (root growth) were markedly higher than the relative top growth at the different growth stages. The increased root growth relative to top growth, resulting in relatively high PAWC values at young growth stages, is the result of water stress induced during those stages.

Other possible mechanisms related to the temporary recovery of the plants over a longer period are the following:

Firstly, the presence of an extremely dry soil layer around the root caused by a quick depletion of water in the root zone as a result of a high evaporative demands. Low hydraulic conductivity from the wetter soil layers to the depleted root zone may be the reason that it takes a few days to restore the equilibrium (Boedt & Laker, 1985). However, this mechanism did not work when the plants were at flowering stage.

Secondly, the shrinkage of the root diameter, resulting in a loss of contact between root surface and soil, under climatic conditions characterized by high evaporative demand (Larcher, 1980; Klepper, 1983). When the root regains it original diameter only after a long time interval then it is possible that the plant will only recover after this long time interval. Again this mechanism failed to work with wheat under stress conditions at flowering stage.

Thirdly, if evaporative demand is very high on the day on which water stress occurs then the stomata may remain closed enabling the plant to recover during the day and the following night. Proof of this was found by Ceulemans et al. (1988b) in maize plants planted in well-watered plots under climatic conditions characterized by a high evaporative demand.

Although the yields obtained at the stressed plots were generally lower than those from the respective control plots, no significant differences could be found. However, a least significant difference of 1 ton/ha (unprotected, p=0,05) indicated that the yield of the plants stressed at the appearance of the flag leaf (end of stage 9 according to Large, 1954) was significantly lower than the yield of the control plots. During their study on the effects of water stress at different growth stages on the yield of wheat, Human & De Bruyn (1988) also failed to find significant differences although yields of stressed plants were generally lower than those of the non-stressed plants except when moderate stress was induced at tillering stage. Similar results were found by Singh & Malik (1983).

3.3.2 Durum wheat

Both stem elongation and PLWP were very good indicators of FMS in young plants. At later growth stages (appearance of flag leaf) stem elongation failed to indicate FMS, but PLWP indicated it very clearly. Again single PLWP values could not be used as an indication of FMS. When PLWP is used as an indicator of FMS, a long-term intensive pattern, starting as soon as possible after irrigation, with daily measurements has to be studied. PLWP measurements on plants of a well-watered control plot made identification of FMS easier as climatic influences could be eliminated. As in the case of wheat PLWP indicated FMS in young plants as soon as the values dropped to -800kPa.

Great care has to be taken as to which leaves are selected for leaf water potential measurements. Tests have shown that young, immature leaves have lower LWP values and could mistakenly be interpreted as an indication of FMS. It is therefore very important to standardize the procedure of PLWP measurements even to the point of leaf selection. This statement was also made by Boedt & Laker (1985) as a consequence of the results obtained during their research on PAWC of different crops in different soils. During this study the youngest, mature leaves were selected for PLWP determinations.

In most cases PLWP and stem elongation measurements indicated FMS simultaneously during the young growth stages. However, during the early vegetative stages (end of tillering) stem elongation indicated first material stress before the pre-dawn leaf water potential at site D6. It is therefore recommendable to use both parameters when determining onset of first material stress in durum wheat during vegetative growth stages.

The PAWC values determined at the different growth stages indicated that the maximum PAWC value (PAWC at flowering stage) is already reached quite some time before flowering. During this study it was found that the maximum PAWC was already reached when the flag leaf started to appear. This means that the PAWC value determined at flowering stage can be used for irrigation scheduling purposes already at the end of the tillering stage (50 days after planting). Before that time a PAWC value of 75% of the PAWC at flowering can be used.

Water stress during the vegetative stages affected vegetative growth and yield severely. The damage caused by water stress at any growth stage was permanent. The plants did not recuperate upon rewatering even if water stress had occurred very early in the growing season (tillering stage). The detrimental effects of water stress during the vegetative stages on vegetative growth and especially on yield clearly show that water stress should be avoided, unless the soil profile allows for a deep and well developed effective root system. Both vegetative growth and yield were less affected at site D16 where the effective root system was found to be the deepest. The reason for this was the presence of boulders and rocks throughout the soil profile which made it easier for the roots to penetrate into the deeper soil layers.

During this study the behaviour of durum wheat under water stress conditions was compared to that of wheat. Four differences were identified:

Firstly, no oscillations of PLWP in durum wheat were found during the drying cycles. These oscillations illustrate the ability of a plant to recover partially (See paragraph 3.4.1). After FMS was reached, PLWP of durum wheat remained low (-1000kPa) when the drying cycle was prolonged. Wheat showed oscillations.

Secondly, PLWP of young, immature durum wheat leaves was constantly lower than that of mature leaves even on well-watered plots. In wheat no difference between mature and immature leaves were measured.

Thirdly, durum wheat plants did not recuperate after water stress had been induced during the vegetative stages. Water stress had a permanent effect on stem elongation and grain yield. Durum wheat was very sensitive to water stress during the early vegetative stages and both stem elongation and yield were affected. In wheat this was not the case.

Fourthly, the PAWC of durum wheat was lower than the PAWC of wheat at every growth stage. The PAWC of durum wheat at flowering stage was about 85% of the PAWC of wheat at flowering stage. Similar differences in PAWC were found by Hensley & De Jager (1982) with maize and sorghum. The ratio of the PAWC of sorghum to that of maize was also about 85%. Durum wheat extracted water slower than wheat and FMS was reached at the same time after irrigation. This is, interestingly enough, again identical to the sorghum/maize comparisons of Hensley & De Jager (1982).

3.3.3 Maize

Leaf expansion and PLWP clearly indicated FMS during the early vegetative stages, i.e. before the 16-leaf stage (70 days after planting). However, serious doubts exist about the indication of FMS by PLWP during the early vegetative stages during the 1985-1986 season. Firstly, because of the hail damage it was impossible to verify the onset of first material stress with leaf expansion data. Secondly, the PAWC values were not consistent with those found during the 1986-1987 season. As in the case of wheat and durum wheat, PLWP values at first material stress during young growth stages (until 14 leaf stage) were at about -800kPa.

Ceulemans et al. (1988a) found that PLWP was not as sensible in indicating FMS as the net carbon-dioxide exchange rate (NCER), especially under climatic conditions characterized by a high evaporative demand (see also Dwyer & Stewart, 1984 and Boedt & Laker, 1985). However, Ceulemans and co-workers conducted a short-term study and based their conclusions on single, daily PLWP measurements. It is very important to realize that when using PLWP as an indicator for FMS daily measurements, starting as soon as possible after irrigation, must be used over an extended period.

Once the plants were past the 16-leaf stage, PLWP values below -1000kPa clearly indicated FMS. Leaf expansion rates were not a reliable parameter for FMS from this growth stage onwards.

The existence of a seasonal variation in PLWP as propagated by Lorens et al. (1987) was also found during this study. As the plants reach maturity, PLWP values tend to be lower than during the young vegetative stages, even under optimal conditions. Bennie (UOFS, personal communication) also found that mature maize plants do not reach the high PLWP values found in younger plants, even under optimal conditions. This was also found with wheat and durum wheat.

PAWC values found during the 1986-1987 season showed that the maximum value is already reached at the 14-leaf stage, quite some time before flowering stage. This was not found during the 1985-1986 season, but doubts exist about the validity of the latter values as they were even lower than would be expected from the root length index at the specific growth stages according to the model of Botha et al. (1983). The plants were severely damaged by hail during the early vegetative stages, resulting in a decrease photosynthetic area. The decrease in photosynthetic assimilates possibly resulted in a slower root development.

The fact that maximum PAWC was reached before the full development of the top growth illustrates again that water stress during vegetative stages stimulates root growth. This means that the close relationship between root growth and top growth found by Erickson (1976), Botha et al. (1983), Muller (1988) and Van Antwerpen (1988) is affected if the plants have been exposed to water stress. Water stress during the vegetative growth stages results in a repartitioning of the assimilates to the roots, favouring root growth (Lang & Thorpe, 1976) and increasing PAWC.

PAWC of maize was higher than that of wheat and a ratio of PAWC wheat to PAWC maize of 92% was found. This is similar to the ratio found by Hensley & De Jager (1982). Boedt & Laker (1985) found that PAWC of wheat and maize were comparable with a generally higher PAWC for wheat. They, however, did studies mainly on fine sandy soils which tend towards higher bulk densities and soil strengths. Under such conditions root development of maize is restricted more than that of wheat.

Leaf expansion and stem elongation were significantly reduced when plants were exposed to soil water stress during the vegetative stages. This was also found by Denmead & Shaw (1960), Acevedo et al. (1971) and Human & De Bruyn (1988). The effects of water stress on leaf expansion decreased as the plants neared maturity and were minimal at the 16-leaf stage. This was confirmed by the results obtained by Human & De Bruyn (1988). Contradictory to the results obtained with wheat, growth of leaves of plants which had experienced water stress during the early vegetative stages did not exceed the growth of the control plants upon rewatering. Consequently, the leaf area as well as the height of the stressed plants was significantly smaller than that of the control plants. Acevedo et al. (1971) stated that the growth of water stressed maize plants after rewatering is merely the resumption of a postponed event and that the truly compensatory rapid growth only lasts a fraction of an hour and does, therefore, not contribute to the total leaf area. Denmead & Shaw (1960) also found that maize plants which had been subjected to water stress during the vegetative stages were shorter than non-stressed plants at the end of the growing season.

During the 1987-1988 experiments it was found that stem elongation in maize was a more sensitive parameter to indicate FMS than leaf expansion. Stem elongation data could make the distinction between moderate and severe water stress and indicated water stress where leaf expansion failed. Stem elongation is easier to measure and allows for more plants to be monitored. It is, however, very important to measure the distances on the stem between successive leaves in order to identify the onset of FMS. The total height of a plant will indicate whether the plant has been subjected to stress or not, but can not indicate at what time water stress was imposed.

Although significant differences in vegetative growth as a result of water stress were found, no significant differences in yield could be detected (See also Chapter 4, maize 1987-1988 season). This contradicts the results of Robins & Domingo (1953) and Denmead & Shaw (1960) who found significant differences (at a 5% probability level) in yield of stressed maize plants compared to non-stressed plants. Denmead & Shaw (1960) reported that "grain yield was affected more than any other plant characteristic by moisture stress at all stages of growth". However, it must be taken into account that the experiments by Denmead & Shaw (1960) were done in containers, while during this study 128 plants per plot (1987-1988 season) and 45 plants per plot (1985-1986 and 1986-1987 seasons) were harvested for yield determinations. Hensley & De Jager (1982) also criticized the use of containers by Denmead & Shaw by proving that the soil available to each plant in the field was about 12 times more than in the containers. Ritchie (1973) considered the difference in root density to be the main reason for the discrepancies between his results (obtained with field experiments) and those of Denmead & Shaw. Denmead & Shaw (1960) attributed the decrease in grain yield to the reduction of the photosynthetic surface if water stress was applied during the vegetative stages and to a reduction in photosynthesic assimilates (used for grain production) if stress was applied during the reproductive frowth stages. The results obtained during this study confirmed the statements of Dwyer & Stewart (1984,1985). They found that a decrease in leaf area or biomass as a result of water stress does not necessarily mean a reduction in yield or productivity.

CHAPTER 4

IRRIGATION SCHEDULING EXPERIMENTS

4.1 INTRODUCTION

Hillel (1980) stated that the main questions concerning irrigation management are "when" to irrigate and "how much". The answers to these questions are very complex and involve the interrelationships between soil, water, crop and climate. An extensive overview of literature on the history of irrigation scheduling was given by Boedt & Laker (1985).

In the past the main objective of irrigation scheduling studies was to maximize yield per unit area and research was mainly concentrated on yield-evapotranspiration relationships. This research pointed out that any irrigation scheduling which reduces evapotranspiration will also reduce yield (Wenda & Hanks, 1981; Hanks, 1982 and English & Nakamura, 1982). Hillel (1980) concluded that one should irrigate as frequently as is practicable. This conclusion is valid if water is not a limiting factor. However,. due to climatic hazards (droughts) and an increased use of water by urban users (industrial and domestic) water has become or is becoming a limiting factor in many areas. This resulted in shifting the aim of irrigation scheduling studies towards maximizing water use efficiencies without significantly reducing yield per unit area. A possible way of maximizing water use efficiencies is to extend the intervals between irrigations (Montgomery, according to Laker, 1983). This implied the definition of the "optimum soil water deficit" or the "allowable depletion". Bucheim & Ploss (1977) defined this quantity of water as " the soil water that may be utilized from the root zone without causing plant stress or yield reduction". However, plant water stress does not always result in yield reduction, as will be shown in this chapter.

The definition of the critical proportion of the available water in the soil profile was approached in different ways by various researchers. The traditional approach defined this proportion as the water held between soil water tensions of 10kPa or 33kPa (field capacity) and 1500kPa (permanent wilting point). This approach is too simple and it has been proven that some crops reach permanent wilting point at soil water tensions much higher than 1500kPa (Chapter 1). Nevertheless, this approach is still used by many researchers, who define the "allowable depletion" as a certain fraction of the available water between field capacity and permanent wilting point. Hsiao, O'Toole & Tomar (1980) stated that this fraction is in most cases chosen by trial-and-error. A detailed discussion and a list of "allowable depletions" for different crops is given by Doorenbos & Kassam (1979).

A more recent approach is the "potential extractable water" (PLEXW) concept of Ratliff, Ritchie & Cassel (1983). In the USA the PLEXW concept is often used for calculating "allowable depletion" (Laker, 1983; Boedt & Laker, 1985). The problem is that purely arbitrary fractions of PLEXW are taken as "allowable depletion". PLEXW itself is unsuitable for irrigation scheduling since the lower limit is taken as the soil water content at which plants die or go dormant due to water stress. The yield losses experienced if such severe stress is induced are too large to be acceptable for an irrigation situation (Boedt & Laker, 1985).

A method for in situ determination of the "allowable depletion" was developed by Bucheim & Ploss (1977). Three values are needed to calculate the allowable depletion. Firstly, the "full value" which is the soil water content after drainage of excess water (i.e. field capacity). Secondly, the "refill level" which is the minimum allowable moisture content in the top 300mm of the soil profile. Thirdly, the "root decimal" which is the ratio of the water extraction from the top 300mm zone to the water extraction from the total soil profile. Soil water content is measured by means of a neutron hydroprobe or tensiometers. Water stress in plants is assessed with visual symptoms or infra-red sensing. Carter & Conway (undated) modified this method by measuring the soil water content at all depths of the soil profile. This method developed by Bucheim & Ploss (1977) and modified by Carter & Conway (undated) is extensively used in areas served by the American Bureau of Reclamation and has yielded higher water use efficiencies (Carter & Conway, undated).

Another approach to determine "allowable depletion" was the use of PAW or the "plant available water". Green (1982) found that 70 to 75% of PAW could be depleted without significantly reducing yield. However, PAW is similar to the PLEXW-concept of Ratliff et al. (1983) in the way that it has severe limitations for direct use in irrigated agriculture because the lower limit is too low (Boedt & Laker, 1985).

The study of PAW by Green (1982) formed the basis for the development of the PAWC-concept by Hensley (1984). Hensley (1984) stated that irrigation scheduling should be based on the amount of water that has been consumed when the crops have reached "well defined stress". PAWC is intended to serve as a definite measurement of "allowable depletion", instead of using an arbitrary fraction of "available water" or "PLEXW" (Boedt & Laker, 1985). The validity of PAWC for irrigation scheduling was tested by Hensley (1984) for wheat and maize at maturity in sealed plots. Yields on plots which were irrigated when an amount of water equal to PAWC for the site was extracted were almost identical to yields on plots which were frequently irrigated (control plots). Unfortunately, no statistical proof of the significance of this finding is available. Hensley (1984) concluded from these experiments that: "PAWC is a valid parameter for irrigation scheduling".

The PAWC-concept was further tested by Boedt & Laker (1985). They conducted several irrigation scheduling experiments during the 1983 winter and 1983-1984 summer seasons at the Vaalharts and Loskop irrigation schemes. The main objective of the research was to determine the effect of irrigation, at extraction of different, arbitrarily chosen fractions of PAWC, on seasonal water use, yield and water use efficiency (Boedt & Laker, 1985). They found a strong relationship between seasonal water use and yield. The reduced seasonal water use as a result of extending the intervals between irrigations was accompanied by a reduction in yield and consequently water use efficiencies were not improved. As long as a certain threshold fraction of PAWC was not exceeded, prolonged irrigation intervals did not significantly reduce yields. This is of extreme importance for two aspects of irrigation scheduling. Firstly, extending the intervals between irrigations can save on the fixed costs that accompany each irrigation (English & Nakamura, 1982). Secondly, the threshold value beyond which yields drop significantly will indicate to what level soil water can be depleted if one is aiming for an optimum irrigation scheduling method (Boedt & Laker, 1985).

An involuntary deficit irrigation resulted in high water use efficiencies and more research in this field was recommended (Boedt & Laker, 1985).

The answer to the question of when to irrigate also depends on the sensitivity of the plants to soil water stress at different growth stages. This has been extensively discussed in Chapter 1. Research on this subject was done during the study of PAWC at different growth stages (Chapter 3) and more experiments establishing the effect of soil water stress at different growth stages on yield will be discussed in this chapter.

4.2 GENERAL RESEARCH PROCEDURES

The irrigation scheduling experiments were conducted at site ISO where two irrigation furrows serve two adjacent areas, ISO-A and ISO-B. ISO-A and ISO-B have 28 and 32 plots of 50 square meters each respectively (Figure 4.1). The aims of the experiments were threefold: firstly, to determine the threshold fraction of PAWC beyond which yields drop significantly. Secondly, to field test deficit irrigation scheduling. Thirdly, to identify degrees of soil water stress sensitivity at different growth stages and the effect of these on yield. The experiments were done with wheat and maize during the 1985 to 1988 winter and summer seasons. A small experiment with durum wheat was conducted during the 1986 winter season. Relevant climatical data for the duration of the experiments are given in Table 2.2 (Chapter 2).

All crops were planted manually because the plots were too small for mechanical planting. General agronomic

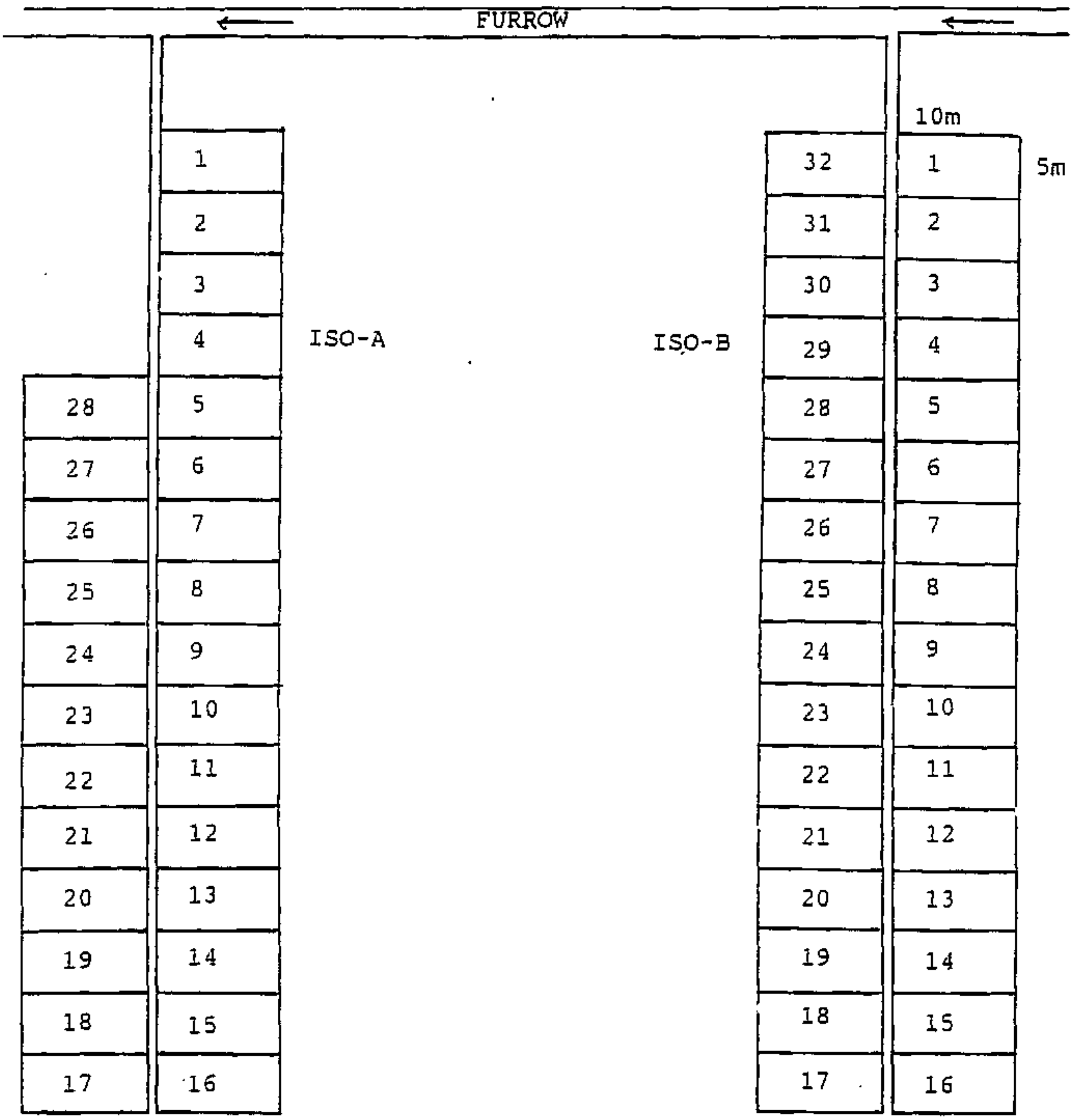


FIG.4.1. GROUND PLAN OF IRRIGATION SCHEDULING SITE ISO.

practices are described in Chapter 2 (Section 2.4.4). More detailed information regarding agronomic practices for each experiment are given in Appendices 2.2.2, 2.2.4, 2.2.6, 2.2.8, 2.2.10 and 2.2.11. A border surrounding all plots was also planted to reduce the "oasis effect". It was technically impossible to cover the plots for protection against rain except during the 1987-1988 summer experiments with maize. An electrical fence was erected around the plots for protection against animals. A description of the rain shields for maize is given in Chapter 2. The main measurements done during the experiments were soil water content and pre-dawn leaf water potential. These techniques are described in detail in Chapter 2.

Wheat and durum wheat were harvested mechanically while maize was harvested manually. Only the central part (8m by 3m) of each plot was used for yield determinations to avoid influences of treatments on adjoining plots. The moisture content of maize grain was determined regularly and crops were harvested when the moisture content was less than 16%. Maize cobs were put in labelled bags and hung in a well aerated barn to dry. The bags could not be left on the floor because of the danger of the grain being eaten by rodents. Yield determinations were done when the moisture content of the grains was 12,5%.

For the statistical analysis of the data the method for data with a single criterion of classification described by Steel & Torrie (1980) was used. The type of analysis is the analysis of variance for any number of groups with equal replication. For some experiments the analysis of variance for any number of groups with unequal replication was used as some plots could not be used because of a poor stand caused by factors not inherent to the treatments. For the calculations the statistical tables compiled by Stoker (1974) were consulted. Due to soil variability a completely random design was used. The variations in the soil properties did not follow a certain spatial direction and it was therefore not suitable to use a randomized complete block design. Yields, applied water and seasonal water consumption for each experiment are given in Appendices 4.1.1 to 4.1.7.

4.3 RESULTS

4.3.1 Wheat and durum wheat

4.3.1.1 1985 winter season

During the 1985 winter season an irrigation scheduling experiment with wheat was conducted at site ISO-A where

28 plots were planted (Figure 4.1). The aim of the experiment was to determine the threshold fraction of PAWC beyond which yields drop significantly and to compare the respective water use efficiencies. At the time of the experiment PAWC of wheat had not been determined yet and was estimated using the model for wheat for soils containing more than 20% silt + clay developed by Boedt & Laker (1985). Regular soil water content monitoring on the plot used for in situ PAWC determination indicated that the plants extracted water up to a depth of 1100mm. Calculation of PAWC using the Boedt & Laker model for a rooting depth of 1100mm gave a PAWC value of 179mm. A PAWC value of 179mm was, therefore, used.

The six treatments, each with four replications, were intended to be as follows:

treatment 25: refilled to field capacity when 25% of PAWC was extracted.

treatment 50: refilled to field capacity when 50% of PAWC was extracted.

treatment 75: refilled to field capacity when 75% of PAWC was extracted.

treatment 100: refilled to field capacity when 100% of PAWC was extracted.

treatment 125: refilled to field capacity when 125% of PAWC was extracted.

treatment def: refilled with 50% of PAWC when 100% of PAWC was extracted. This is a typical example of deficit irrigation.

Later in the season it was found that the real PAWC for wheat at this site was 144mm (in situ determination). Consequently, the intended water extractions of 25%, 50%, 75%, 100% and 125% were in reality water extractions of 30%, 60%, 95%, 125% and 150% respectively and the six applied treatments can be redefined as follows:

treatment 30: refilled to field capacity when 30% of PAWC was extracted.

treatment 60: refilled to field capacity when 60% of PAWC was extracted.

treatment 90: refilled to field capacity when 90% of PAWC was extracted.

treatment 125: refilled to field capacity when 125% of PAWC was extracted.

treatment 150: refilled to field capacity when 150% of PAWC was extracted.

treatment def: refilled with 60% of PAWC when 125% of PAWC was extracted.

The different treatments were started at flowering stage and continued until the wheat started drying. Until the start of the experiment at flowering all plots were irrigated regularly to avoid soil induced water stress in the plants. Unfortunately, heavy rains during early summer seriously interfered with the experiment and water extraction never proceeded beyond about 90% of a PAWC of 144mm. Only treatments 30, 60 and 90 could be applied and they received respectively 3, 2 and 1 irrigation after the start of the experiment. The other treatments were never irrigated after flowering and can therefore be considered as the same treatment. No definite conclusions in regard to treatments 125, 150 and def could, therefore, be drawn. Rust infestation and delayed harvesting, caused by persistent heavy rains, drastically reduced yields.

Yields and water use efficiencies for both applied water (WUEi) and total seasonal consumption (WUEt) are listed in Table 4.1 and differences between WUEi means are given in Table 4.2. Extending the intervals between irrigations did not reduce yield significantly but did not improve water use efficiencies based on total water consumption either. However, water use efficiencies for applied water (WUEi) for treatments 125, 150 and def (which were in fact identical treatments) were very similar and highly significantly higher than the WUEi for treatment 30, the treatment which received the most frequent irrigations. Although the WUEi means of treatments 125, 150 and def were not significantly different from the WUEi means of treatments 60 and 90, the former three treatments did give slightly higher WUEi values than the latter two.

The frequent full irrigation treatment (treatment 30) gave the lowest yield and WUEi. Possible explanations for this are temporary water logging in the root zone upon each irrigation as a result of poor drainage and a partial leaching of nutrients from the root zone by rain water

TABLE 4.1 - Yield and water use efficiencies for applied water (WUEi) and total water consumption (WUEt) of different irrigation treatments with wheat (1985 winter season)

Treatments	Yield (ton/ha)	WUEi (kg/mm/ha)	WUEt
30	2,60	3,78	2,75
60	3,06	5,03	3,55
90	2,86	4,45	3,17
125	2,83	5,29	3,33
150	2,94	5,42	3,41
def	3,16	5,69	3,73
lsd (p=0,05)	ns	1,00	ns
lsd (p=0,01)	ns	1,37	ns

TABLE 4.2 - Differences between WUEi means of different irrigation treatments with wheat (1985 winter season)

Treatments	30	90	60	125	150
def	1,91**	1,24*	0,66	0,40	0,27
150	1,64**	0,97	0,39	0,13	
125	1,51**	0,84	0,26		
60	1,25*	0,58			
90	0,67				

** = significant at 1% level
 * = significant at 5% level

4.3.1.2 1986 winter season

During the 1986 winter season an irrigation scheduling experiment with wheat and durum wheat was conducted at site ISO-B (Figure 4.1). The aim of the experiment was to assess if deficit irrigation would significantly improve water use efficiencies without reducing yield. A PAWC value of 144mm, as determined in situ during the 1985 winter season, was used. No PAWC values for wheat at young growth stages were available. The PAWC for treatment 100yg-50 during young growth stages had to be determined during the experiment. This was done by regular pre-dawn leaf water potential measurements and soil water content monitoring. When FMS was identified for the first time (shortly before tillering stage) a PAWC value of 45mm was found. When tillering was completed a PAWC value of 80mm was found. When FMS was identified for the third time (shortly before full canopy stage) the PAWC was 120mm. Thereafter the PAWC value of 144mm was used and a 50% extraction-50% refill treatment was applied. Because of the poor results obtained during the previous season, the high frequency full irrigation treatment was replaced by the 50% extraction treatment (treatment control). The PAWC value for durum wheat was 124mm.

The six treatments for wheat, each with four replications were as follows:

treatment control: refilled to field capacity when 50% of PAWC was extracted.

treatment 50-75: refilled with 50% of PAWC when 75% of PAWC was extracted.

treatment 25-100: refilled with 25% of PAWC when 100% of PAWC was extracted.

treatment 50-100: refilled with 50% of PAWC when 100% of PAWC was extracted.

treatment 75-100: refilled with 75% of PAWC when 100% of PAWC was extracted.

treatment 100yg-50: refilled to field capacity when 100% of PAWC was extracted at young growth stages (before full canopy was reached), thereafter refilled to field capacity when 50% of PAWC was extracted.

The three treatments with durum wheat, each with three replications were as follows:

treatment control: refilled to field capacity when 50% of PAWC was extracted.
treatment 50-100: refilled with 50% of PAWC when 100% of PAWC was extracted.
treatment 50-75: refilled with 50% of PAWC when 75% of PAWC was extracted.

All treatments, except 100yg-50, were started at full canopy stage. All plots were irrigated regularly before the start of the treatments. Yield, WUEi and WUEt for each treatment are listed in Table 4.3.

Although yields and water use efficiencies were much higher than those obtained during the previous season, they were lower than expected in view of the good season and great care to optimize other production conditions. No significant differences in yield and WUEt between treatments were found. In other words deficit irrigation failed to imprcve water use efficiencies based on total consumption, contradicting the results of Miller (1977) and the lysimeter studies done at Fort Hare (Boedt & Laker, 1985). However, significant differences in water use efficiencies based on applied water (WUEi) between treatments were found for wheat (Table 4.4). The highest WUEi was found for deficit treatments 25-100 and 50-100, but only WUEi of treatment 25-100 was significantly higher than those of the other treatments.

TABLE 4.3 - Yield and water use efficiencies based on applied water (WUEi) and total water consumption (WUEt) of different irrigation treatments with wheat and durum wheat (1986 winter season)

Treatments	Yield (ton/ha)	WUEi (kg/mm/ha)	WUEt
control	5,22	10,24	7,57
50-75	4,89	9,98	6,89
25-100	4,48	12,63	6,60
50-100	4,41	11,75	7,54
75-100	3,95	10,26	6,64
100yg-50	5,00	9,44	7,15
lsd (p=0,05)	ns	2,06	ns
durum wheat			
control	4,75	10,79	7,30
50-100	4,34	8,68	6,03
50-75	4,12	9,58	6,70
lsd (p=0,05)	ns	ns	ns

TABLE 4.4 - Differences between WUEi means of different irrigation treatments with wheat (1986 winter season)

Treatment	100yg-50	50-75	control	75-100	50-100
25-100	3,19*	2,65*	2,39*	2,37*	1,38
50-100	1,81	1,27	1,01	0,99	
75-100	0,82	0,28	0,02		
control	0,80	0,26			
50-75	0,54				

* = significant at 5% level

In view of their own results, and especially those of Miller (1977) and others, Boedt & Laker (1985) suggested that best water use efficiencies would probably be obtained with so-called "frequent deficit irrigation". This concept amounts to frequent light irrigations in a soil water range close to FMS. The good WUEi results obtained with treatment 25-100 in the present study support the frequent deficit irrigation theory. It was better than the full irrigation (control) treatment and the less frequent deficit irrigation treatments (e.g. 75-100). The frequent deficit irrigation, 25-100, gave a no less than 23.3% increase in WUEi over the well-watered control.

Deficit irrigation in combination with mild water extraction (treatment 50-75) did not have any beneficial effects.

4.3.1.3 1987 winter season

During the 1987 winter season an irrigation scheduling experiment with wheat was conducted at site ISO-A (Figure 4.1). The experiment was aimed at determining the effect of soil water stress at different growth stages on yield. It followed a logical sequence to the results obtained with the young growth stage experiments at sites D6, D12 and D16 (see Chapter 3). Three growth stages, during which drying cycles were started, were chosen on basis of the results obtained with the young growth stage experiments. For each stage moderate and severe soil water stress was imposed on the plants. The seven treatments, each with four replications were as follows:

treatment control: refilled to field capacity when 50% of PAWC was extracted.

treatment 100t: drying cycle started at beginning of tillering (stage 2 according to Large, 1954) and extraction of 100% of PAWC. Moderate stress at stage 5 (leaf sheaths strongly erected).

treatment 125t: drying cycle started at beginning of tillering (stage 2 according to Large, 1954) and extraction of 125% of PAWC. Severe stress at stage 7 (first node of stem visible).

treatment 100tf: drying cycle started when tillers were formed and leaf sheaths started to lengthen (stage 4 according to Large, 1954) and extraction of 100% of PAWC. Moderate stress at stage 8 (flag leaf just visible).

treatment 125tf: drying cycle started when tillers were formed and leaf sheaths started to lengthen (stage 4 according to Large, 1954) and extraction of 125% of PAWC. Severe stress at stage 10 (ear in boot).

treatment 100b: drying cycle started when "ear was in boot" (stage 10 according to Large, 1954) and extraction of 100% of PAWC. Moderate stress shortly before flowering.

treatment 125b: drying cycle started when "ear was in boot" (stage 10 according to Large, 1954) and extraction of 125% of PAWC. Severe stress at flowering and grain filling.

The term "PAWC" used in the description of the treatments must be understood as the PAWC value for wheat at that particular growth stage. The onset of FMS, corresponding per definition with an extraction of 100% of PAWC, was regularly checked by means of PLWP measurements. For treatments 100t and 125t the PAWC value was 100mm. FMS, indicated by PLWP readings, occurred at soil water extractions between 140mm and 150mm for treatments 100tf and 100b, confirming the in situ determined PAWC value of 144mm. Before and after the respective drying cycles, plots were frequently irrigated (at extraction of 50% of PAWC) to avoid soil induced water stress during growth stages other than the one that was being studied during the specific treatment.

Yields were similar to those obtained during the previous season (Compare Tables 4.3 and 4.5). Water use efficiencies, both for applied water (WUEi) and total consumption (WUEt), were markedly higher during this season than during 1986, however (Tables 3.4 and 3.5). The 1987 WUEt values are high compared to values usually found for wheat (e.g. Boedt & Laker, 1985 ; and others). A possible explanation for the good 1987 values is the fact that temperatures during September 1987 (monthly average maximum of 21,1 C) were generally lower than during Sept. 1986 (monthly average maximum of 24,9 C). September 1987 was also characterized by a high rainfall figure (70.5mm).

Moderate stress, i.e. extraction of 100% PAWC, did not in the least affect yields, the results for all three growth stages being remarkably similar to that for the well-watered control (Table 4.5). Hensley (1984) developed the PAWC concept with the intention that it should indicate the maximum quantity of water that could be extracted from the soil between irrigations without significantly reducing yields. Successful application of this concept is strongly dependent on correct identification of FMS, the lower limit of PAWC. The results of the present study indicate that FMS was not exceeded during any of the "100%" PAWC extractions.

None of the severe soil water stress treatments caused statistically significant reductions in yield (Table 4.5). The yield for 125t, i.e. "severe stress" during the youngest growth stage tested, was in fact practically identical to that for the well-watered control. This could be an indication that PAWC was in fact under-estimated for this growth stage. During the later growth stages yields did decline where severe stress was induced and for 125b the average yield was quite low (only 68% of that for the well-watered control). Although the differences were not statistically significant they do probably indicate danger signs in regard to soil induced water stress.

TABLE 4.5 - Yield and water use efficiencies based on applied water (WUEi) and total water consumption (WUEt) of different irrigation treatments with wheat (1987 winter season)

Treatments	Yield (ton/ha)	WUEi (kg/mm/ha)	WUEt
control	5,66	13,32	8,92
100t	5,37	14,31	9,41
125t	5,61	14,96	9,75
100tf	5,65	17,39	10,57
125tf	4,96	18,02	10,27
100b	5,66	17,40	10,57
125b	3,85	14,01	8,76
lsd (p=0,05)	ns	3,33	ns

TABLE 4.6 - Differences between WUEi means of different irrigation treatments with wheat (1987 winter season)

Treatments	control	125b	100t	125t	100tf	100b
125tf	4,70*	4,01*	3,71*	3,06	0,63	0,62
100b	4,08*	3,39*	3,09	2,44	0,01	
100tf	4,07*	3,38*	3,08	2,43		
125t	1,64	0,95	0,65			
100t	0,99	0,30				
125b	0,69					

* = significant at 5% level

WUEi values for treatments 100tf, 125tf and 100b were markedly higher than those for all other treatments (Table 4.5). All three were statistically significantly higher than those for the well-watered control and treatment 125b, i.e. severe stress induced at flowering and grain filling (Table 4.6). The low WUEi for the well-watered control was due to high total irrigation levels giving the same yield as for 100tf and 100b. The low WUEi for treatment 125b was due to the low yield caused by the severe water stress induced at flowering and grain filling stages. Both the yields and WUEi values for treatments 100tf and 100b are remarkably similar.

4.3.2 Maize

4.3.2.1 1985-1986 summer season

An irrigation scheduling experiment with maize similar to the 1985 winter experiment with wheat was conducted at site ISO-B during the 1985-1986 summer season (see Figure 4.1). The aim of the experiment was to assess the threshold fraction of PAWC that can be extracted by the plants without significantly reducing yields and also to determine the effect of extending intervals between irrigations on yield. At the time of the experiment no PAWC value for maize was available. It was then decided to use the PAWC of wheat (144mm) which was determined in situ at this site. Previous research has shown that in most cases differences between PAWC of wheat and PAWC of maize are very small (Hensley & De Jager, 1982; Boedt & Laker, 1985). The real PAWC for maize at flowering stage was determined later during the experiment, and was found to be 149mm. The difference between PAWC used for the experiment (144mm) and the real PAWC (149mm) was very small and the applied treatments were thus equal to those defined.

Six treatments, each with four replications, were as follows:

treatment 25: refilled to field capacity when 25% of PAWC was extracted.
treatment 50: refilled to field capacity when 50% of PAWC was extracted.
treatment 75: refilled to field capacity when 75% of PAWC was extracted.
treatment 100: refilled to field capacity when 100% of PAWC was extracted.
treatment 125: refilled to field capacity when 125% of PAWC was extracted.
treatment def: refilled with 50% of PAWC when 100% of PAWC was extracted.

The treatments were started when the maize had reached full canopy stage and were ended when the maize started to dry (indicated by the change in leaf colour and the drop in water extraction). Before the start of the experiments all plots were frequently irrigated to keep the soil water content at an optimum level. Heavy rains interfered with the experiment during the early summer months, November and December, and the soil profile was above field capacity level for some time, leading to drainage losses of water. This was taken into account when the total seasonal water consumption was calculated and the necessary corrections were made. Yield and water use efficiencies for both applied water (WUEi) and total consumption (WUEt) are listed in Table 4.7.

Both yields and water use efficiencies were quite high. Neither extending the intervals between irrigations, nor deficit irrigation improved water use efficiencies based on total consumption or, reduced yields significantly. However, the water use efficiency for applied water (WUEi) of treatment def (the deficit irrigation) was significantly higher than for all other treatments (Table 4.8). Furthermore the values for treatments 125 and 25 were significantly higher than those of treatments 50 and 75.

TABLE 4.7 - Yield and water use efficiencies based on applied water (WUEi) and total water consumption (WUEt) of different irrigation treatments with maize (1985-1986 summer season)

Treatments	Yield (ton/ha)	WUEi	WUEt (kg/mm/ha)
25	10,37	19,95	12.05
50	9,85	16,84	10,35
75	9,21	16,60	9,94
100	9,77	18,98	11,13
125	8,70	20,24	10,68
def	9,06	23.53	11,69
lsd (p=0,05)	ns	2,93	ns
(p=0,01)	ns	4,01	ns

TABLE 4.8 - Differences between WUEi means of different irrigation treatments with maize (1985-1986 summer season)

Treatments	75	50	100	25	125
def	6.93**	6.69**	4.55**	3.58*	3.29*
125	3.64*	3.40*	1.26	0.29	
25	3.35*	3.11*	0.97		
100	2.38	2.14			
50	0.24				

** = significant at 1% level
 * = significant at 5% level

4.3.2.2 1986-1987 summer season

The good results obtained with the deficit irrigation treatment during the previous season (see paragraph 4.3.2.1) justified further research into this aspect. Consequently, an irrigation experiment with the emphasis on deficit irrigation was conducted at site ISO-A during the 1986-1987 summer season (see Figure 4.1). The aim of the experiment was to determine which deficit irrigations would give the best applied water use efficiencies without significantly reducing yields. A PAWC value of 149mm, as determined during the 1985-1986 summer season, was used. Six treatments, each with four replications were as follows:

treatment control; refilled to field capacity when 30% of PAWC was extracted.

treatment 30-50: refilled with 30% of PAWC when 50% of PAWC was extracted.

treatment 30-75: refilled with 30% of PAWC when 75% of PAWC was extracted.

treatment 50-75: refilled with 50% Of PAWC when 75% of PAWC was extracted.

treatment 75-75: refilled to field capacity when 75% of PAWC was extracted (control treatment for 75% of PAWC extraction).

treatment 75-100: refilled with 75% of PAWC when 100% of PAWC was extracted.

The treatments were started when the plants had reached full canopy stage and were ended when the plants started drying (indicated by the drop in water uptake and the change in leaf colour). A severe hailstorm after flowering stage damaged the plants very badly, resulting in moderate yields. Yield and water use efficiencies for both applied water and total consumption and were determined for each treatment (Table 4.9).

Yield. WUEi and WUEt were lower than during the previous season. Although yield was not reduced by the deficit irrigation treatments, water use efficiencies for total consumption were not improved. Treatments control, 50-75 and 30-75 all gave significantly higher WUEi values than treatments 75-100 and 75-75 (Table 4.10). This means that high frequency irrigations, including "frequent deficit" irrigations (previously propagated by Laker, 1983 and Boedt & Laker, 1985) in general gave better results than low frequency full and deficit irrigations.

If the results of the 1986 wheat experiment (Section 4.3.1.2) were available when this experiment was planned, deficit irrigations in the range of 100% PAWC extraction (e.g. 25-100, 50-100, etc.) would probably have been used in this experiment. The latter could possibly have given better WUEi results than the milder 30-75 and 50-75 treatments.

TABLE 4.9 - Yield and water use efficiencies based on applied water (WUEi) and total water consumption (WUEt) of different irrigation treatments with maize (1986-1987 summer season)

Treatments	Yield (ton/ha)	WUEi	WUEt
		(kg/mm/ha)	
control	8,34	13,34	8,64
30-50	8,44	11,81	7,97
30-75	8,10	12,75	8,06
50-75	9,34	13,34	8,85
75-75	8,85	10,73	7,63
75-100	8,00	10,59	7,14
lsd (p=0,05)	ns	1,75	ns

TABLE 4.10 - Differences in WUEi means for different irrigation treatments with maize (1986-1987 summer season)

Treatments	75-100	75-75	30-50	30-75	control
50-75	2,75*	2,61*	1,53	0,59	0,00
control	2,75*	2,61*	1,53	0,59	
30-75	2,16*	2,02*	0,94		
30-50	1,22	1,08			
75-75	0,14				

* = significant at 5% level

4.3.2.3 1987-1988 summer season

The aim of this irrigation experiment, conducted at site ISO-B, was to study the effect of moderate and severe soil water stress at different growth stages on yield and to identify stress sensitive periods. The experiment follows a logical sequel to the results obtained with the young growth stage experiments at sites D6, D12 and D16 (Chapter 3). The nature of the experiment was to impose moderate and severe soil water stress at three different growth stages. The onset of first material stress was detected by means of regular pre-dawn leaf water potential measurements. A PAWC value of 110mm was found for treatment 100-4 for which FMS was detected at the 11 leaf stage. PAWC values for treatments 100-10 (FMS at flowering stage) and 100-15 (FMS at grain filling stage) were between 145mm and 155mm, confirming the value of 149mm for mature maize found during the 1985-1986 summer season.

Eight treatments, each with four replications, were as follows:

treatment control: refilled to field capacity when 30% to 50% of PAWC was extracted.
treatment 100-4: drying cycle started at four leaf stage and 100% of PAWC extracted.
treatment 125-4: drying cycle started at four leaf stage and 125% of PAWC extracted.
treatment 100-10: drying cycle started at ten leaf stage and 100% of PAWC extracted.
treatment 125-10: drying cycle started at ten leaf stage and 125% of PAWC extracted.
treatment 100-15: drying cycle started at fifteen leaf stage and 100% of PAWC extracted.
treatment 125-15: drying cycle started at fifteen leaf stage and 125% of PAWC extracted.
treatment 50-75: deficit irrigation, refilled with 50% of PAWC when 75% of PAWC was extracted.

Before and after a drying cycle, the relevant plots were frequently irrigated to keep the soil water content at an optimum level. All drying cycles were started with the soil profile at field capacity. During the drying cycles rain shields were put over the plots for protection against rain (Chapter 2).

Yields and water use efficiencies (Table 4.11) were almost identical to those obtained during the 1985-86 summer season (also at site ISO-B). Yields were somewhat higher and water use efficiencies markedly higher than those obtained at site ISO-A during the hail-affected 1986-87 summer season (Compare Tables 4.7, 4.9 and 4.11).

TABLE 4.11 - Yield and water use efficiencies, based on applied water (WUEi) and total consumption (WUEt) of different irrigation treatments with maize (1987-1988 summer season)

Treatments	Yield (ton/ha)	WUEi	WUEt
		(kg/mm/ha)	
control	10,37	19,76	12,57
100-4	10,03	19,11	11,96
125-4	9,46	21,01	13,19
100-10	9,68	20,39	12,14
125-10	9,00	20,01	11,32
100-15	9,98	19,02	12,50
125-15	8,05	16,96	10,51
50-75	9,51	18,12	11,12
lsd (p=0,05)	ns	ns	ns

No significant differences in yield and water use efficiencies were found between treatments (Table 4.11). Yields for the 125% extractions were consistently slightly lower than for the corresponding 100% extractions. For the 125% extraction at grain filling (treatment 125-15) this difference was fairly clear and

WUEi was also markedly lower than for the other treatments (although none of these differences were statistically significant). These trends are consistent with similar trends found during previous seasons.

4.4 DISCUSSION AND CONCLUSIONS

The quite good maize yields, averaging close to 10t/ha, obtained during the 1985-86 and 1987-88 summer seasons at site ISO-B were achieved despite conditions, especially in regard to quality of the soil, that are apparently far from ideal for maize production. Even at site ISO-A, where severe crusting and moderate salinity conditions prevail (Chapter 5), yields of close to 9t/ha were obtained during the hail-affected 1986-87 season. These results are consistent with the yields in excess of 10t/ha obtained at sites D12 and D16, and even D6 with its far from ideal soil (Chapter 3), and with the good yields generally obtained by other researchers at the Cradock Experimental Station.

PAWC, defined as the amount of extractable water between FC and FMS based upon identification of FMS by means of pre-dawn leaf water potential measurements, proved to be a reliable parameter for use in the design of irrigation scheduling strategies for maize. Yields were not reduced significantly even at extraction of 100% of PAWC. This is in contrast to the results of Boedt & Laker (1985), who found considerable maize yield losses at extraction of 100% PAWC. They concluded that it was for maize not wise to extract more than 71,5% of PAWC before applying the next irrigation. The overestimation of PAWC for maize was explained by the inaccuracy of pre-dawn leaf water potential as a parameter for identification of FMS under climatic conditions of extremely high evaporative demand (Boedt & Laker, 1985). They concluded that "under such conditions crops suffer considerable water stress before it is indicated by pre-dawn leaf water potential". Contrary to expectations, climatic conditions comparable with the extremes experienced during the research of Boedt & Laker (1985) at Vaalharts were not found during the research period at Cradock reported here. This probably explains the differences between the present results and those of Boedt & Laker (1985).

Although extraction of 125% of PAWC for maize did not result in statistically significant lower yields, there was a consistent tendency for yields at this level of extraction to be somewhat lower than those for other treatments (Tables 4.7 and 4.11). This must be seen as a clear warning that such extraction is excessive and that 100% PAWC should be taken as the absolute lower limit of plant-available water for irrigation purposes.

In contrast to the fairly good yields obtained with maize, the yields of wheat and durum wheat were moderate to poor, averaging slightly less than 5t/ha in 1986 and slightly more than 5t/ha in 1987 (Tables 4.3 and 4.5). This was despite great care to optimize production conditions and following the advice of researchers who were consistently obtaining high yields with wheat and durum wheat at the same research station during the same seasons. The soil at site ISO has an extremely severe crusting problem, a factor known to have a serious adverse effect on the emergence of wheat. At site ISO-A, where most of the wheat research was done, moderate salinity problems also exist which might have had a significant effect. Similar moderate to poor yields were also obtained at sites D6, D12 and D16 (Chapter 3).

In the case of wheat extraction of 100% of PAWC again, as in the case of maize, did not reduce yields (Tables 4.1, 4.3 and 4.5). This agrees with the results of Boedt & Laker (1985) for wheat and confirms the validity of PAWC, based upon FMS determined by means of pre-dawn leaf water potential measurements, as a parameter for irrigation scheduling for wheat.

Deficit irrigation failed to improve water use efficiencies based upon total water consumption (WUEt) for both maize and wheat. This contradicts the results of Miller (1977) and Boedt & Laker (1985). However, water use efficiencies based upon applied water (WUEi) were generally improved significantly by deficit irrigation practices (Tables 4.3 and 4.9). There was a clear tendency for high frequency deficit irrigation to give the best results in this regard. High frequency deficit irrigation around FMS (100% extraction of PAWC) gave better results than high frequency deficit irrigation combined with mild water extraction (e.g. extraction of 75% of PAWC). All these findings regarding deficit irrigation have very important practical and economic implications in regard to irrigation scheduling and especially irrigation system design. This will be outlined in Chapter 6.

A third aspect studied during the irrigation scheduling experiments was the influence of soil water stress at different growth stages on yield and water use efficiencies for wheat and maize (Tables 4.5 and 4.11). Because of the quite large quantities of water that both maize and wheat could extract during drying cycles started at young growth stages before going into stress it was in fact not possible to study stress effects at young growth stages. Stress. therefore, only occurred at relatively advanced growth stages. For both maize and wheat moderate water stress (extraction of 100% of PAWC) did not reduce yields at any growth stage, contradicting the results of researchers such as Singh & Malik (1983) and Human & De Bruyn (1988). During the late vegetative stages even severe stress (125% of PAWC extracted) did not reduce yields. This differs from the results of Denmead & Shaw (1960).

Severe water stress at the flowering and grain filling stages reduced yields in both crops, although the reductions were not always statistically significant. The reductions during the grain filling stages were particularly severe. The latter is in agreement with the findings of Robins & Domingo (1953) and Classen & Shaw (1970), who indicated a high degree of sensitivity to water stress during grain filling. These authors also reported less damaging effects by water stress during vegetative stages. Prolonged water stress during grain filling decreased the assimilation rate of the plant and enhanced leaf senescence.

CHAPTER 5

STUDIES ON MISCELLANEOUS ASPECTS RELATED TO THE PAWC RESEARCH OF THE PRESENT STUDY

5.1 INTRODUCTION

The research reported in Chapters 2, 3 and 4 was conducted at sites that were far from ideal for this type of research. They do, however, represent widespread real-life situations for which answers need to be found. These non-ideal situations necessitated some additional studies and/or expansion and closer attention to certain aspects normally studied in conjunction with PAWC research.

The aspects which received special attention include:

a. At site D16 difficulties inserting aluminium neutron probe access tubes were encountered because of the presence of rocks and boulders in the subsoil. This led to the conclusion that filled up gullies (dongas) were present at this site. A simple method was used to delineate these filled up gullies.

b. The relatively poor and spatially highly variable yields obtained at site ISO-A led to special studies indicating relatively high soluble salt contents in the soils of some plots. The relationships between salt content, yield and irrigation regime was, therefore, studied for this site.

c. The latter led to a further study aimed at assessing the influence of heavy irrigations combined with gypsum applications on the leaching of soluble salts from this soil.

d. Because of the different drainage characteristics at the different sites and the possible implications of slow drainage for water uptake in the wet range of PAWC, i.e. close to "field capacity", drainage curves were determined for the soils at all four sites.

e. Information regarding root densities at different depths are useful for explaining water extraction patterns. The results of studies done by prof.

A.T.P. Bennie of the U.O.F.S. and his co-workers at some of the sites during the present study are reported briefly.

5.2 RESEARCH TECHNIQUES

5.2.1 Delineation of filled up gullies at site D16

A grid of equidistantial lines 1 meter apart was layed out over the experimental area at site D16. At each intersection point a hole was drilled to a maximum depth of 1500mm by means of a standard soil auger with a 50mm diameter. Where rocks or boulders hindered the augering, the depth at which they occurred was noted. The result was a bird's-eye view of the plots at site D16 which clearly showed the location of the filled up gullies.

5.2.2 Relationships between yield and soluble salts at site ISO-A

On every plot at site ISO-A a sample of topsoil (0-300mm) was taken in four places. The four samples were mixed and 500g was kept for analysis. The same procedure was followed for subsoil (700-900mm) sampling. The soil electrical resistance (saturated paste) of each sample was determined in the laboratoria of the Department of Soil Science and Plant Nutrition at the University of Pretoria.

5.2.3 Leaching of soluble salts at site ISO-A

Four plots at site ISO-A were selected to represent different salt contents. The amounts of soluble salts in the soil on plots 3 and 28 were quite high, while low amounts were found on plots 26 and 27. At each plot two soil samples were taken from top and subsoil at depths of 300mm and 700mm respectively and mixed together for each depth. Thereafter soil samples were taken after every treatment. Care was taken that all samples for each treatment were taken on the same spots in the respective plots. The electrical resistance of saturated pastes and the amounts of soluble Na, K, Ca and Mg of each sample were measured. All analyses were done in the laboratories of the Department of Soil Science and Plant Nutrition of the University of Pretoria.

Plots 28 (with a high salt content) and plots 26 and 27 (both with a lower salt content) received heavy leaching. Plot 3 (with a high salt content) received both gypsum and heavy leaching.

The seven treatments applied on all four plots were:

Treatment 1: sampling and irrigation application of 350mm water to all plots on 18/01/1988.

Treatment 2: sampling, gypsum application of 4 ton/ha on plot 3 and irrigation application of 200mm water to all plots on 26/01/1988.

Treatment 3: sampling, gypsum application of 4 ton/ha on plot 3 and irrigation application of 350mm water to all plots on 03/02/1988.

Treatment 4: sampling, gypsum application of 4 ton/ha on plot 3 and irrigation application of 250mm water to all plots on 11/02/1988.

Treatment 5: sampling and irrigation application of 200mm water to all plots on 18/02/1988.

Treatment 6: sampling and irrigation application of 200mm water to all plots on 07/0301988.

Treatment 7: sampling.

5.2.4 Determination of drainage curves

At each of the four sites an aluminium neutron hydroprobe access tube was inserted in a plot (2m by 2m). After determination of the soil water content by means of a neutron hydroprobe, the plots were irrigated. When all surface water was drained the soil surface was covered with a black plastic sheet to avoid evaporation. Soil water content was regularly monitored at time intervals ranging from 15 minutes during the first three hours after irrigation to 24 hours a few days after irrigation.

5.3 RESULTS AND DISCUSSION

5.3.1 Delineation of filled up gullies at site D16

The location of the filled up gullies is illustrated in Figure 5.1. The numbers indicate the depth at which rocks or boulders, preventing the auger of going deeper, were found. The x-symbol indicates that no rocks or boulders were found to a depth of 1500mm. Delineating filled up gullies is very useful in studies on crop behaviour under different treatments as it can explain why plants behave differently from others in the same plot. It also gives a complete picture of soil variability in the experiment location, allowing for a more accurate sampling and adaptations in statistical analysis if differences within treatments should be unacceptably high.

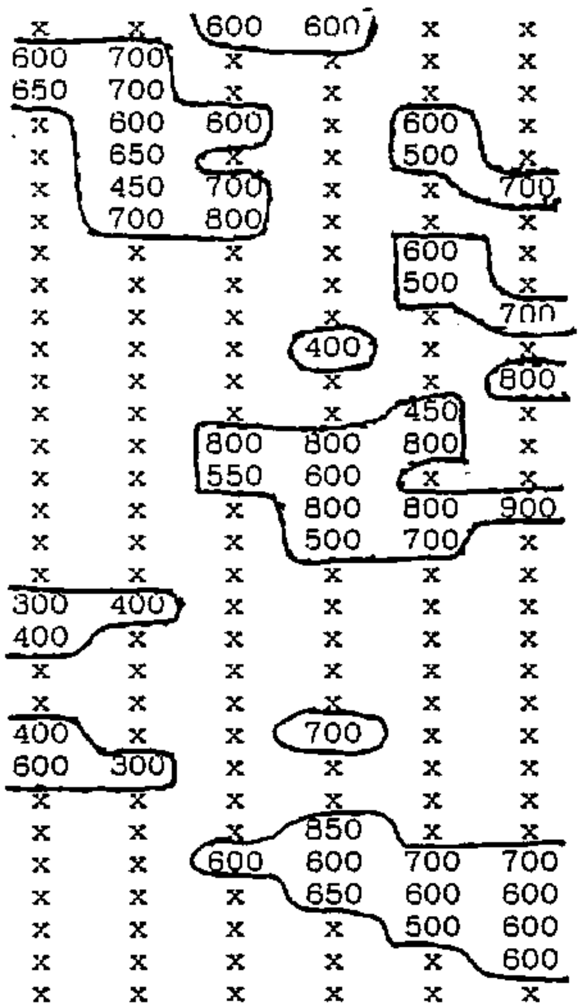


Fig. 5.1 Delineation of filled up gullies at site D16.

5.3.2 Relationship between yield and soluble salts at site ISO-A

The electrical resistance values, measured in saturated pastes, and the corresponding yields for each plot are given in Table 5.1.

The resistances measured in the topsoil were quite satisfactory except for plot 25 where the low value indicated a high amount of soluble salts. This explains why growth on this plot was very poor from early in the growing season. The low electrical resistances, due to a high amount of soluble salts, in the subsoil of certain plots explain why growth on these plots started deteriorating as soon as the roots reached this part of the profile.

No clear relationshop between electrical resistance in the subsoil and yield could be found when all plots were taken into account. The reason for this was the difference in irrigation treatments which also influenced yields. It is therefore necessary to study the effect of salinity on yield for each treatment seperately. These effects are shown in Figures 5.2 and 5.3.

For treatments control and 30-50, where small amounts of

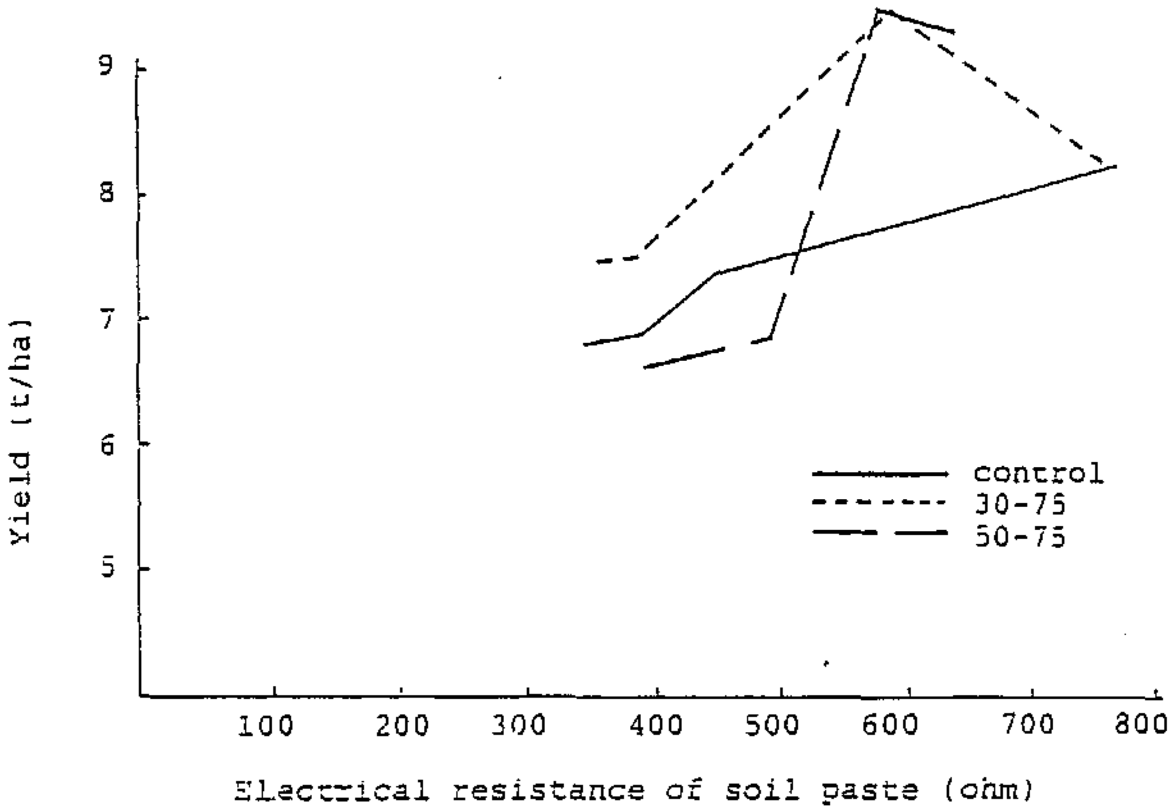


Fig. 5.2 Relationship between yield and salinity for treatments control, 30-75 and 50-75.

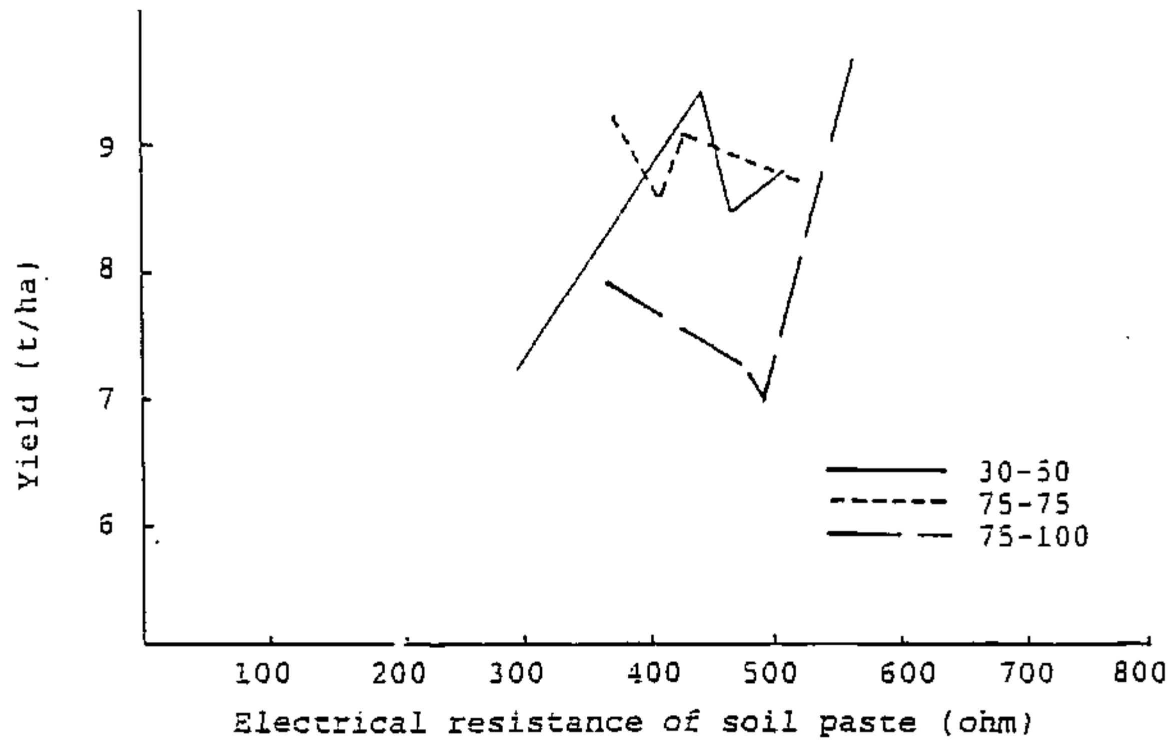


Fig. 5.3 Relationship between yield and salinity for treatments 30-50, 75-75 and 75-100.

water were applied quite frequently, the relationship is clear: the higher the level of salinity (the lower the electrical resistance), the lower the yield. A considerable drop in yield can be expected when electrical resistance values are lower than 450 Ohm. Application of small amounts of water, especially in a deficit irrigation treatment, does not contribute to leaching of soluble salts.

For treatments 30-75, 50-75 and 75-75 the maximum extraction of soil water before irrigation was equal (75% of PAWC), but different amounts of water were applied at each irrigation. Treatment 30-75 received the same amount of water at every irrigation as treatments control and 30-50, but a higher extraction of soil water was required before irrigation. This resulted in lower yields for similar degrees of salinity. Considering the yields of treatment 50-75, where larger amounts of water were applied with every irrigation, it is safe to say that for treatment 30-75 we might already expect a drop in yield for electrical resistance levels of 500-600 Ohm. The application of large amounts of water in treatment 75-75 decreased the effect of salinity on yield (leaching). High yields were obtained even for high degrees of salinity which decreased yields when smaller amounts of water were applied.

Treatment 75-100 involved applications of large amounts of water but only when 100% of PAWC was extracted. This high extraction resulted in a very concentrated soil solution and even for moderate degrees of salinity yields dropped considerably.

TABLE 5.1 - Soil electrical resistance measured in a saturated paste for top and subsoil and yields of maize at site ISO-A (1986-1987 summer season)

Plot	Electrical resistance (Ohm) topsoil	subsoil	Yield (ton/ha)
1	no data	no data	not used
2	480	370	7,41
3	510	380	9,17
4	500	360	7,80
5	490	450	9,35
6	480	650	9,24
7	500	780	9,24
8	460	410	8,55
9	410	400	7,46
10	430	380	7,91
11	480	600	9,46
12	480	380-560	9,70
13	530	600	9,38
14	500	340-580	8,39
15	630	535	8,63
16	530	500	7,07
17	580	420	6,56
18	680	300-500	7,93
19	620	510	8,69
20	540	475	8,46
21	500	490	7,31
22	530	800	8,13
23	480	430	9,06
24	550	525	6,83
25	520	440	not used
26	320	340	not used
27	400	400	not used
28	460	310	7,28

5.3.3 Leaching of soluble salts at site ISO-A

The results of the chemical soil analyses of plots 27 and 28 are presented in Appendix 5.1. The effects of heavy irrigations and gypsum applications are clearly illustrated by the results found on plots 3 and 26 (Figures 5.4 to 5.11).

The electrical resistance increased markedly in the top soil of plot 26 where no gypsum was applied, but no differences were measured in the subsoil. The highest increases in electrical resistance in the top soil of plot 26 were already measured after application of treatments 1 and 2. Thereafter, the values remained fairly constant. The displacement of soluble salts from the topsoil into the subsoil is clearly illustrated by the electrical resistance values (Table 5.2). The soluble salts leached out from the topsoil were merely replacing those leached out of the subsoil and electrical resistance values in the subsoil only started increasing after application of treatment 3. The application of gypsum on plot 3 did not have any effects on the electrical resistance in the top soil (Table 5.2). However, a sharp increase was noted in the electrical resistance of the subsoil after application of treatment 5.

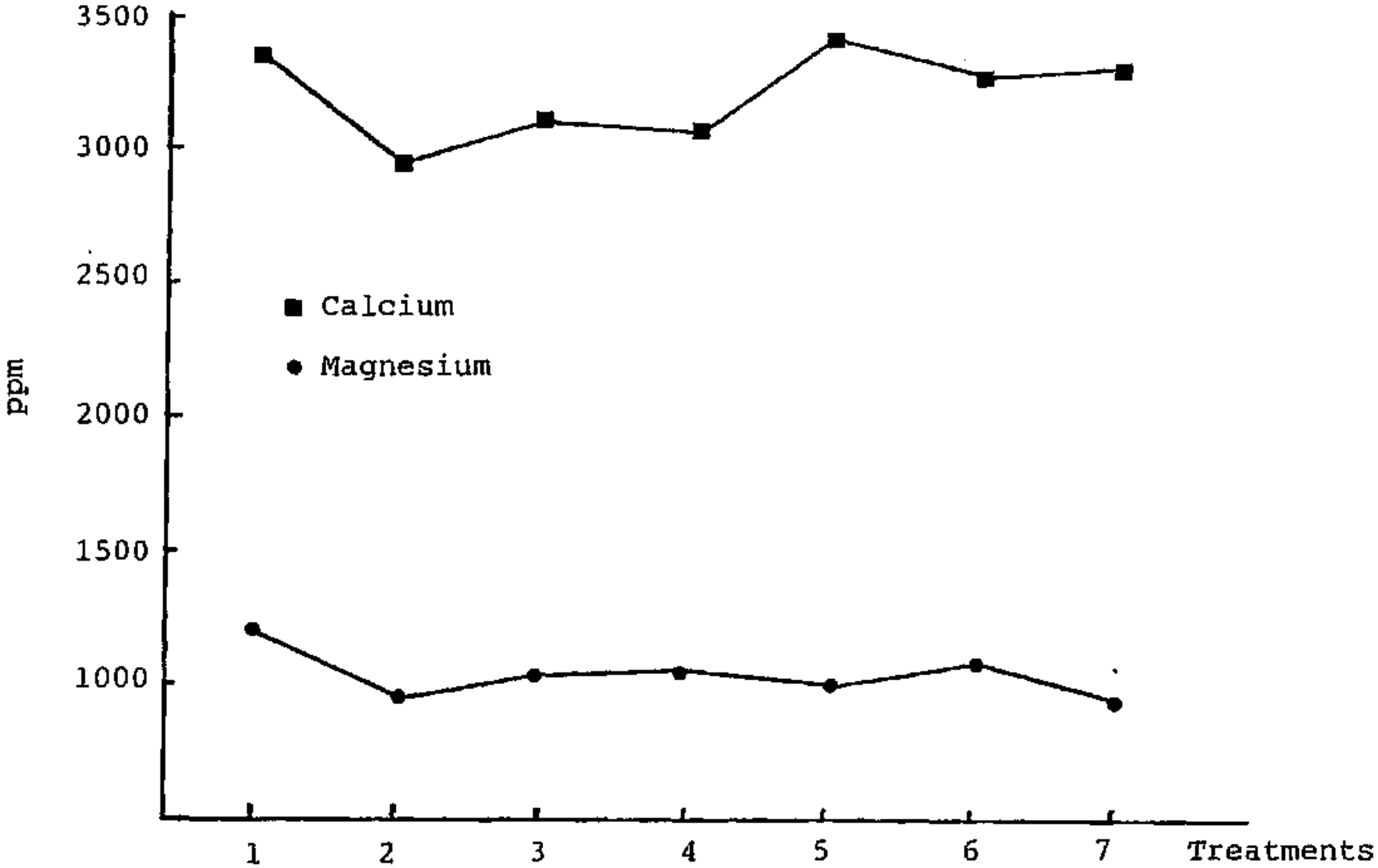


Fig. 5.4 Soluble calcium and magnesium contents in the topsoil of plot 3 for the different treatments.

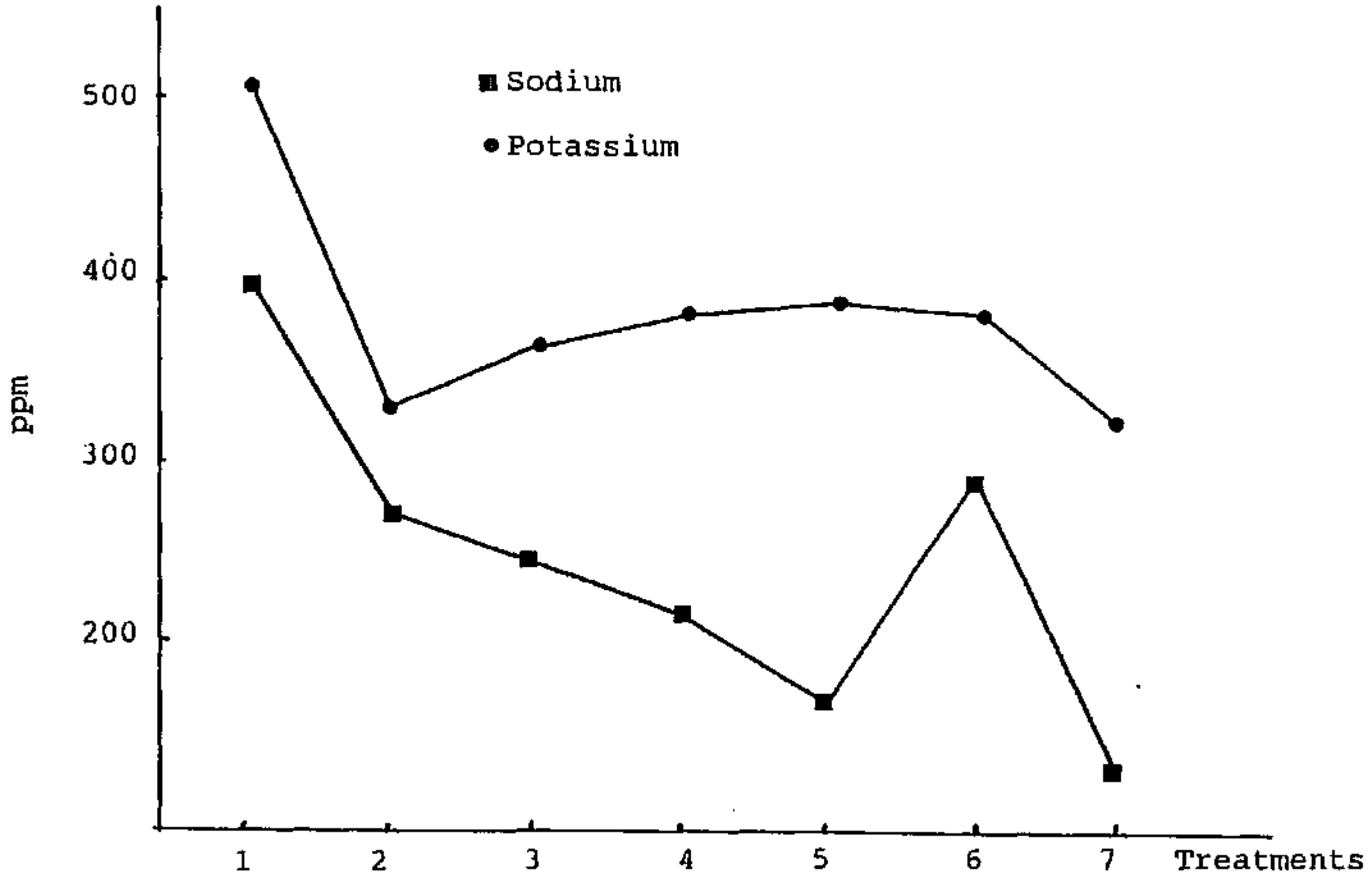


Fig. 5.5 Soluble sodium and potassium contents in the topsoil of plot 3 for the different treatments.

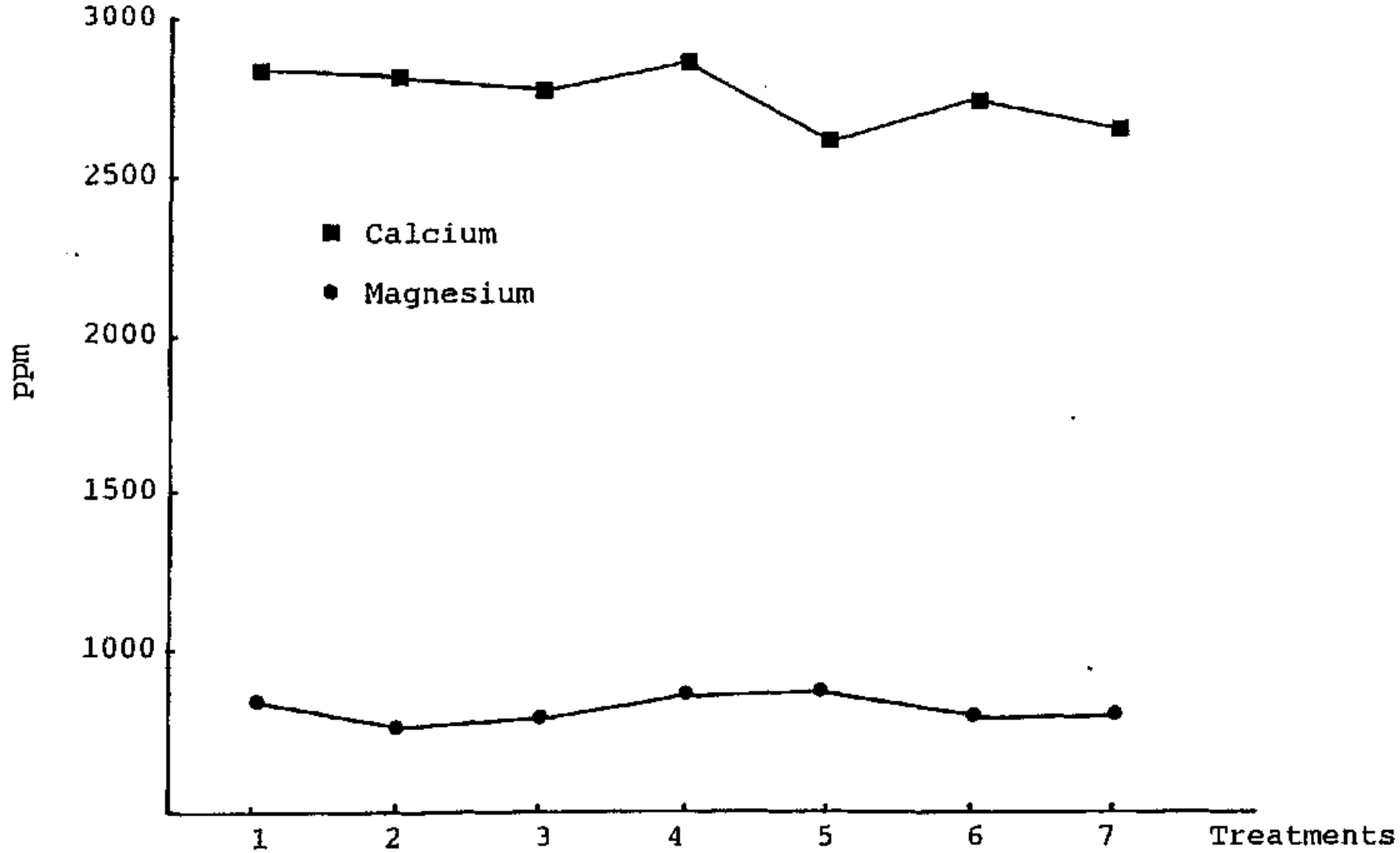


Fig. 5.6 Soluble calcium and magnesium contents in the subsoil of plot 3 for the different treatments.

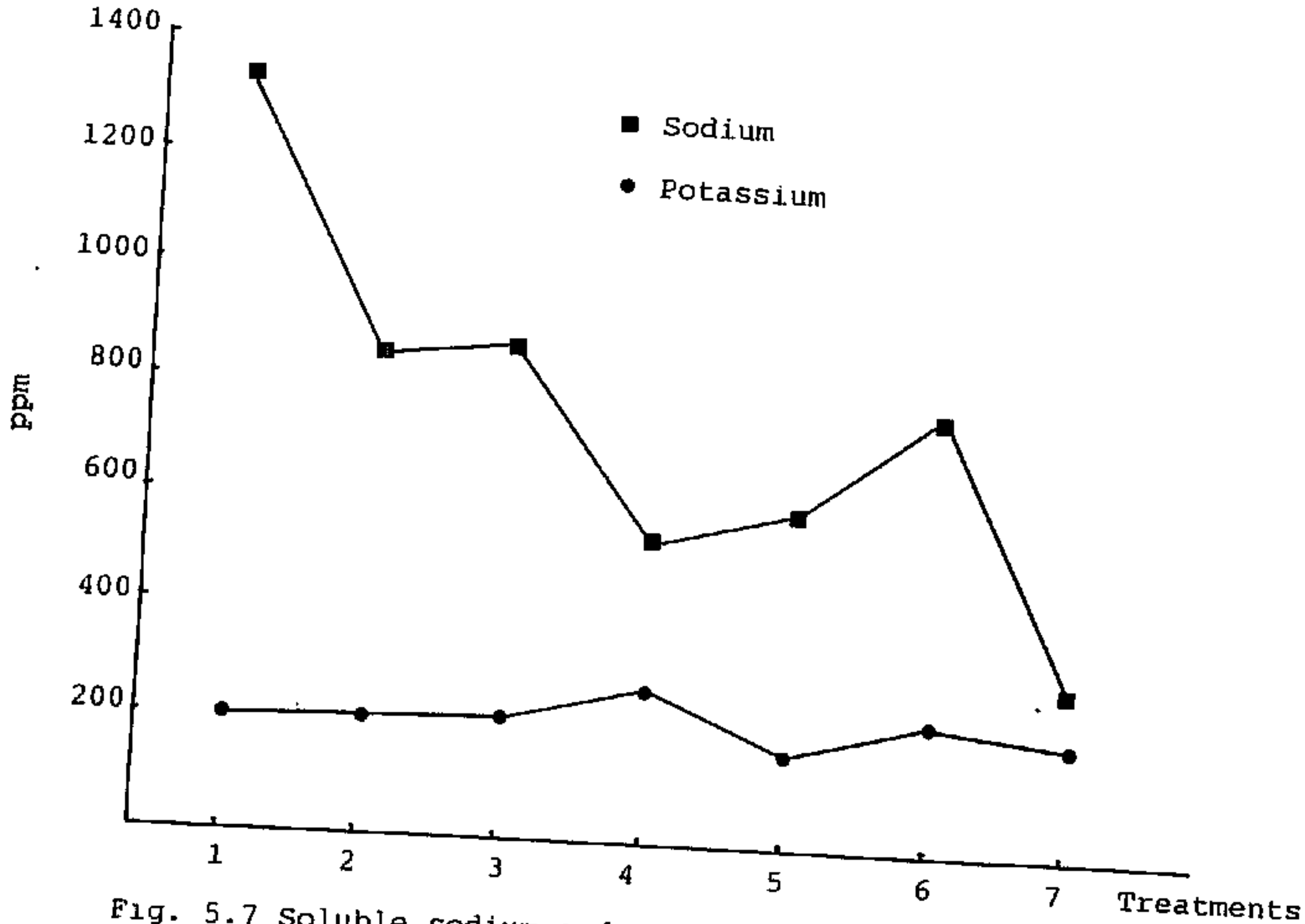


Fig. 5.7 Soluble sodium and potassium contents in the subsoil of plot 3 for the different treatments.

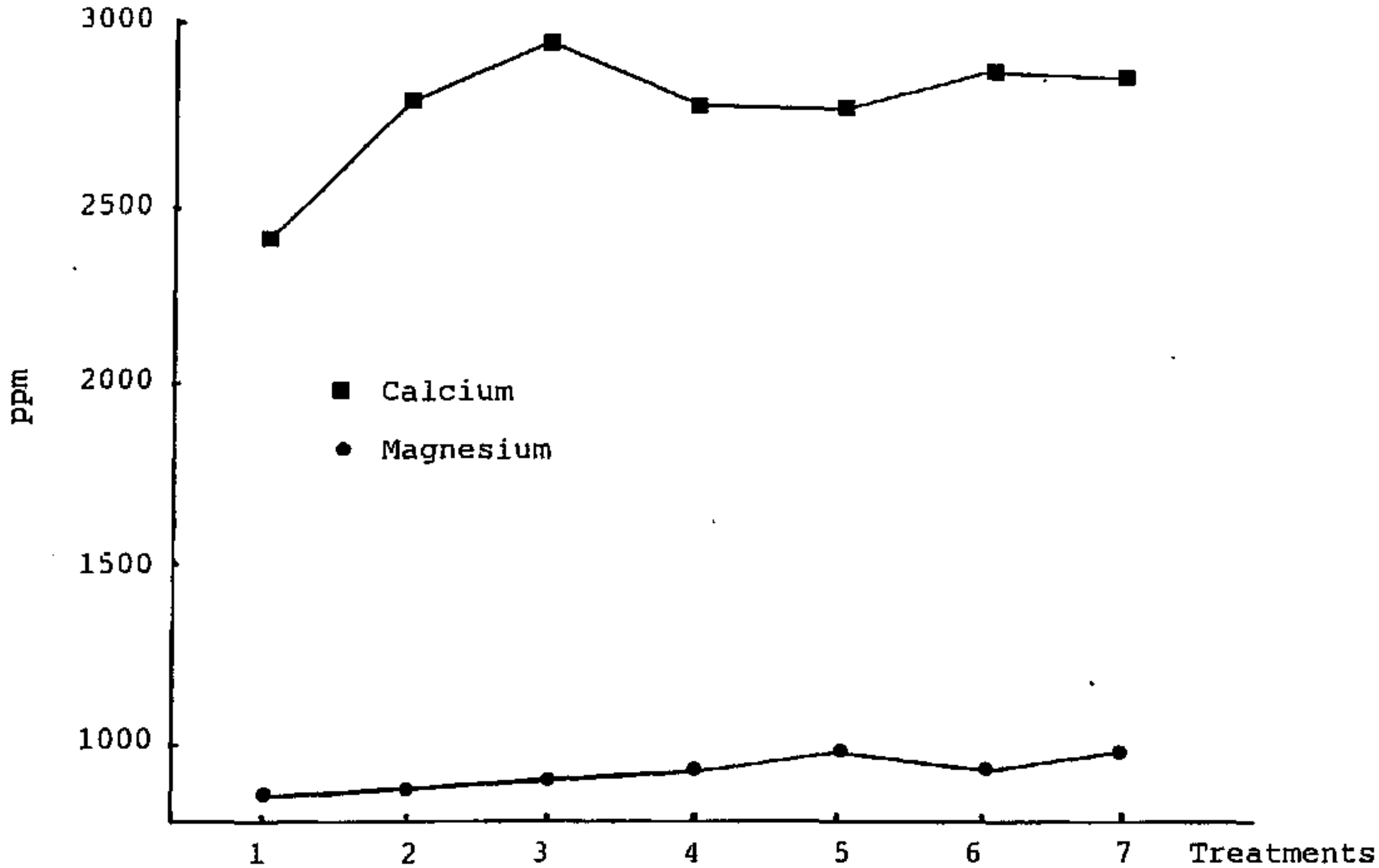


Fig. 5.8 Soluble calcium and magnesium contents in the topsoil of plot 26 for the different treatments.

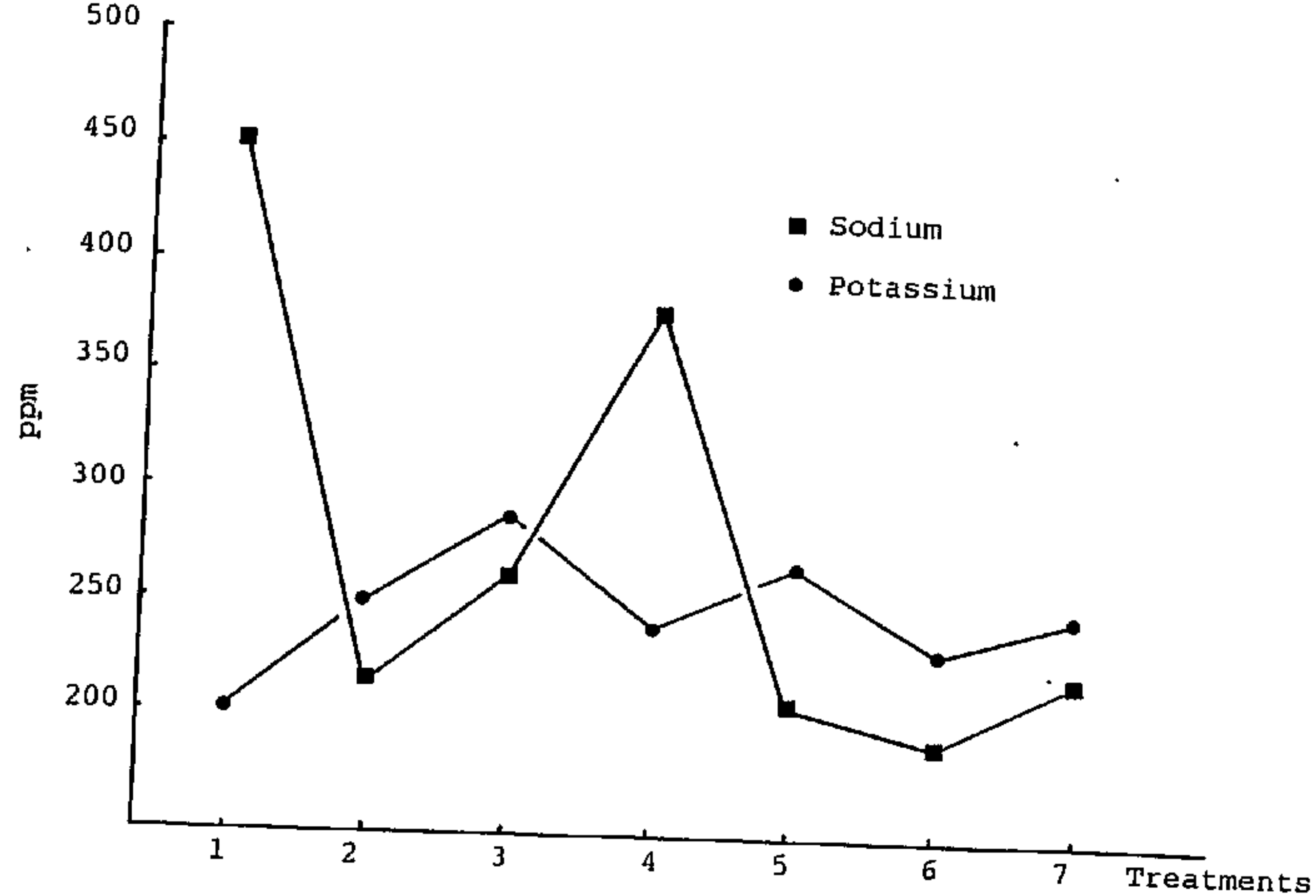


Fig. 5.9 Soluble sodium and potassium contents in the topsoil of plot 26 for the different treatments.

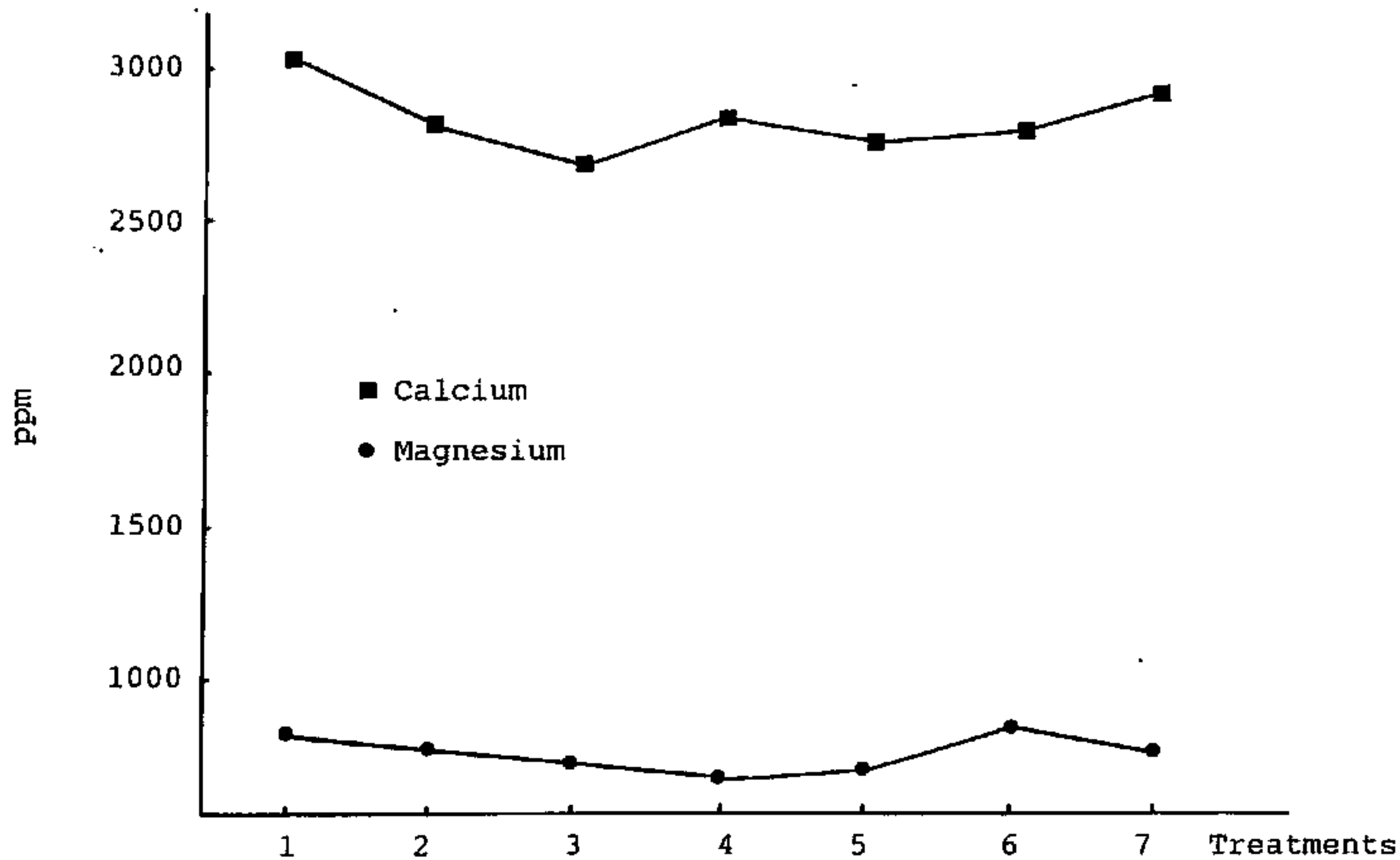


Fig. 5.10 Soluble calcium and magnesium contents in the subsoil of plot 26 for the different treatments.

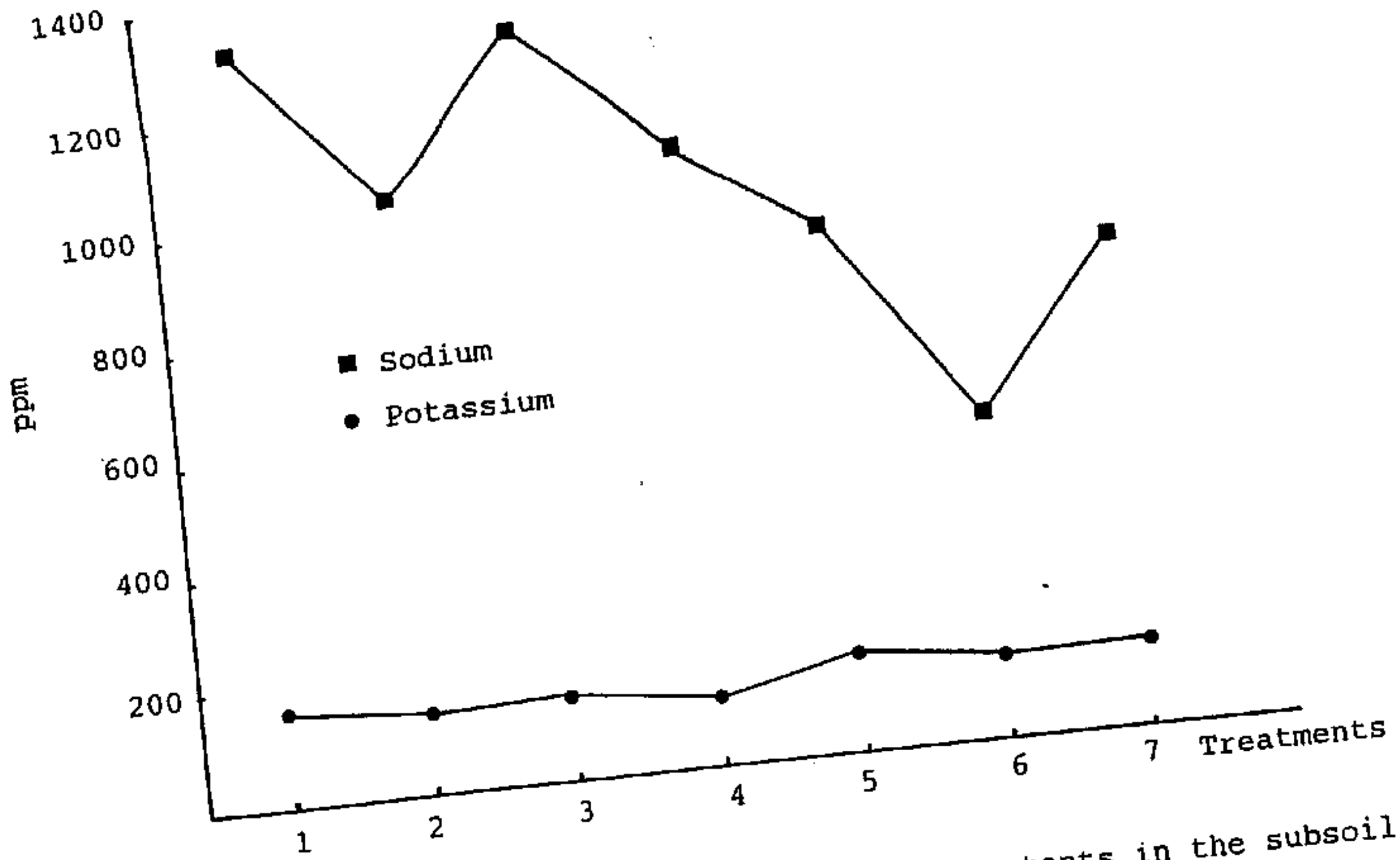


Fig. 5.11 Soluble sodium and potassium contents in the subsoil of plot 26 for the different treatments.

Heavy irrigation treatments did not leach soluble calcium or magnesium out of both topsoil and subsoil on plot 26. Similar results were found on plot 3 where gypsum was applied (Table 5.2).

The application of gypsum on plot 3 had a distinctive effect on the leaching of soluble sodium and potassium. The amounts of sodium in both top- and subsoil were markably decreased at the end of the experiments. The effect of the gypsum application was illustrated by comparison with the results found on plot 26 where no gypsum was applied. The amounts of sodium in both top- and subsoil of plot 26 were comparable to those on plot 3 before the start of the experiments. However, at the end of the experiments the amounts of sodium on plot 26 were considerably higher, especially in the subsoil, than the amounts measured on plot 3 (Table 5.2). The amounts of sodium in the subsoil of plot 26 oscillated strongly during the first four treatments and were only decreasing steadily after the application of four irrigations. This indicates that the application of gypsum contributes strongly to the leaching of soluble sodium as would be expected. Although the results in Table 5.2 could indicate that the application of gypsum might leach out potassium (See topsoil plot 3), two facts indicate that this is not the case. Firstly, the most important decrease was measured before gypsum was applied. Secondly, applications of gypsum in treatments 2, 3 and 4 did not have any effect on the leaching of potassium. It is, therefore, most likely that the value measured before the start of the experiments (508 mg/kg) was wrong.

TABLE 5.2 - Electrical resistances and amounts of soluble Ca, Mg, K and Na measured in top- and subsoil of plots 3 and 26 for the different treatments

Treatment	1	2	3	4	5	6	7
Plot 3							
topsoil							
R (Ohm)	370	580	420	420	290	300	390
Ca (mg/kg)	3356	2966	3126	3072	3440	3284	3342
Mg (mg/kg)	1192	956	1042	1064	984	1100	946
K (mg/kg)	508*	328	364	384	390	382	322
Na (mg/kg)	402	272	242	214	166	292*	126
subsoil							
R (Ohm)	400	450	450	465	460	650	750
Ca (mg/kg)	2834	2804	2772	2868	2620	2748	2652
Mg (mg/kg)	840	744	794	872	872	796	802
K (mg/kg)	194	210	202	270	160*	226	198
Na (mg/kg)	1326	862	880	528	584	782*	302
Plot 26							
topsoil							
R (Ohm)	480	600	700	700	660	730	780
Ca (mg/kg)	2394*	2772	2930	2756	2738	2854	2822
Mg (mg/kg)	846	854	870	920	972*	932	978*
K (mg/kg)	202*	252	288	240	270	232	250
Na (mg/kg)	456	214	260	382*	206	190	220
subsoil							
R (Ohm)	700*	300	400	530	550	730*	560
Ca (mg/kg)	3038	2814	2694	2858	2780	2818	2936
Mg (mg/kg)	846	770	730	698	732	884	776
K (mg/kg)	156	130	144	110	172	144	156
Na (mg/kg)	1322	1050	1316	1090	920	566	864

* = doubtful value

5.3.4 Drainage curves

Drainage curves for the soils at all four sites are illustrated in Tables 5.3 to 5.6. The figures in these tables indicate the soil water contents, expressed as a volume percentage, at different soil depths at different times after irrigation.

The soils at all four sites showed fairly high to high infiltration rates into the upper soil layers and except for site D6, where a compacted layer occurred just below 600mm, also relatively fast drainage. This is contradictory to what was expected for "difficult" soils like these with their high silt and fine sand contents, but in agreement with their unexpectedly low bulk densities. This is also in agreement with the efficient leaching of excess salts found at site ISO.

The pre-irrigation determinations at site D6 (Table 5.3) showed that the layer at 600mm was very dry (in keeping with the intense water extraction found in this layer during PAWC studies - Chapter 3). During the first post-irrigation measurement (2h) the water contents at the 150 and 300mm depths had already almost reached a maximum. By 6h it reached a maximum and by 12h it was already declining, despite the barrier at 600mm. The water content in the 150mm layer kept om declining extremely slowly until the last day of measurement (day 14). In the 300mm layer it declined very slowly until day 4. from when it remained absolutely constant. The decrease in water contents after day 2 was so slow and small that the values for day 2 could be taken as "field capacity" for practical purposes.

In the layers at 450 and 600mm the water contents had also increased sharply by 2h after irrigation and increased dramatically by 6h after irrigation. At this stage both layers were in fact over-saturated with water (i.e. contained water in excess of the calculated total porosity). By 12h the water contents of these layers had already started decreasing. The decrease in water content was very slow and by day 14 the 600mm layer was still over-saturated. The intense water extraction from this layer and good plant performance (especially by maize) on this soil is, therefore, unexpected.

Despite the restricting layer above it the water content in the layer at 750mm showed a slow, gradual increase right from the first measurement and reached a practically constant value already at 36h, which can be taken as field capacity. At 900mm a slow, gradual increase started a little later, but even at this depth the value on day 3 can be taken as field capacity.

In the layer at 1050mm the increase started a little later than at 900mm, as could be expected. The water content in this layer increased sharply between days 2 and 3 and between days 3 and 4 and reached a very high level of 38%, which is very close to saturation (total porosity in this layer being 42%), on day 5. After this it decreased very slowly and was still high even after 14 days. This indicates a secondary restricting layer at this depth, which apparantly also affected rooting depth in this soil (Chapter 3).

At 1200mm field capacity was also reached on day 3, from when on the water content in this layer remained constant. The water contents of the layers below 1200mm remained low, indicating that insufficient water was applied to bring the whole profile to field capacity.

TABLE 5.3 - Soil water content at different soil depths at different times after irrigation at site D6

Depth (mm)	Soil water content (%)								
	dry	2h	6h	12h	24h	36h	2d	3d	4d
150	26	38	41	37	36	34	33	33	31
300	23	35	37	34	34	32	31	29	28
450	23	37	47	45	44	43	43	42	40
600	13	23	61	55	56	54	52	52	52
750	21	22	24	25	28	30	31	32	31
900	19	19	21	22	24	25	27	29	30
1050	16	17	17	19	19	21	26	32	36
1200	18	18	18	18	19	24	26	30	30
1350	19	19	19	19	19	19	19	20	20
1500	21	21	21	21	21	21	21	21	21

Depth (mm)	5d	6d	7d	8d	9d	10d	11d	12d	13d	14d
150	31	30	29	29	28	28	28	28	28	27
300	28	28	28	28	28	28	28	28	28	28
450	40	38	38	37	37	36	35	36	34	33
600	54	50	49	48	47	47	47	47	45	42
750	31	30	30	30	30	30	30	30	29	28
900	31	30	30	30	30	29	29	29	29	29
1050	38	36	36	36	35	35	35	35	35	34
1200	32	30	30	30	30	31	30	30	30	30
1350	20	20	20	20	21	21	22	22	22	24
1500	21	21	21	21	21	21	22	22	22	24

The soil at D12 (Table 5.4) was quite dry before the drainage curve determination was commenced (except in the layers at 750mm and 900mm). In the layers at 150, 300 and 450mm field capacity was reached already at 6h after irrigation. The quantity of water applied was insufficient to bring the layers below 450mm to field capacity. On day 9 a second irrigation was applied to bring the deeper layers to field capacity. The wetting front reached a depth of 1050mm within 24 hours after the second irrigation and a depth of of 1200mm the next day. Although the wetting front reached these deeper layers quickly it was followed by a gradual relatively slow increase in water content. The result was that field capacity was practically reached only after 3 days (day 12) at 900mm, after 4 days at 1050mm and after 6 days at 1200mm. Actual "full values" were reached even later.

In the top layers water infiltration and drainage into the wet soil layers during the second irrigation differed much from that into the dry soil during the first irrigation, as could be expected. After one day the water contents rose sharply, practically reaching field capacity at a depth of 750mm after one day. At the same time the water contents to a depth of 600mm rose above field capacity and then started decreasing slowly to reach field capacity only after four days (day 13) in the

300, 450 and 600mm layers and even later in the 150mm layer.

TABLE 5.4 - Soil water content at different soil depths at different times after irrigation at site D12

Depth (mm)	Soil water content (%)									
	dry	2h	6h	12h	24h	36h	2d	3d	4d	5d
150	12	32	28	28	28	28	28	28	28	28
300	13	27	31	31	30	30	29	29	29	29
450	14	25	30	30	30	31	31	31	31	29
600	16	17	19	20	21	22	22	23	24	24
750	20	20	21	21	21	21	21	22	22	22
900	22	22	22	22	22	22	22	22	22	22
1050	10	10	10	10	10	10	10	10	10	10
1200	9	9	9	9	9	9	9	9	9	9
	6d	7d	8d	*9d	10d	11d	12d	13d	14d	15d
150	28	28	28	28	36	34	33	31	30	29
300	29	29	29	29	34	32	32	31	30	30
450	30	30	30	30	33	33	32	31	31	31
600	24	24	24	24	33	33	32	31	30	30
750	22	23	23	23	29	30	31	31	31	31
900	22	22	22	22	24	26	29	30	30	32
1050	10	10	10	10	16	19	23	29	30	31
1200	9	9	9	9	9	15	23	25	27	29

* = second irrigation.

At site D16 (Table 5.5) the whole profile was very dry before the drainage curve determination was started. The wetting front had reached 600mm by the time the first post-irrigation measurement was made (after 2 hours). By 6 hours the wetting front had reached 750mm and the top 600mm had practically drained to field capacity. The water applied was insufficient to bring the layers below 600mm to field capacity. There was a slow gradual increase in the water contents to a depth of 1050mm and the 750 mm layer was not far below field capacity after 24 hours. As in the case of D12 an additional irrigation was applied on day 9. In the case of D16 the wetting front moved down even faster than at D12, reaching 1500mm within 24 hours. Again the water contents in the top 600mm clearly exceed field capacity for the first two days after irrigating this wet topsoil (in fact causing very marginal air-filled porosities for these two days). By the third day these layers had practically drained to field capacity again (absolutely correct values being reached by the fifth day). The deeper layers filled to field capacity gradually, the time lapse to reach it increasing with depth.

TABLE 5.5 - Soil water content at different soil depths at different times after irrigation at site D16

Depth (mm)	Soil water content (%)								
	dry	2h	6h	12h	24h	36h	2d	3d	4d
150	15	32	31	30	29	28	28	28	28
300	10	33	31	30	30	30	30	30	29
450	10	33	32	32	31	31	31	30	30
600	10	25	31	31	31	30	30	30	29
750	10	11	17	21	27	28	28	28	29
900	11	11	12	12	13	15	18	21	22
1050	12	12	12	12	12	12	14	14	14
1200	9	9	9	9	9	9	9	9	9
1350	9	9	9	9	9	9	9	9	9
1500	9	9	9	9	9	9	9	9	9

Depth (mm)	5d	6d	7d	8d	*9d	10d	11d	12d	13d	14d
150	28	28	28	28	28	35	33	28	28	28
300	27	27	27	27	27	34	34	30	28	27
450	29	29	29	29	29	34	34	31	30	29
600	30	30	30	30	30	36	34	31	31	30
750	29	29	29	29	29	31	32	32	31	31
900	23	23	23	23	23	27	28	31	32	32
1050	15	17	18	18	18	25	29	30	30	31
1200	9	10	10	11	11	18	25	29	30	32
1350	9	9	9	9	9	15	22	27	29	31
1500	9	9	9	9	9	12	18	25	27	30

* = second irrigation.

At site ISO (Table 5.6) great care was taken to ensure that sufficient water was applied to bring the whole profile to field capacity. Before the start of the measurements the top 750mm of the soil was quite dry, the layers at 900 and 1050mm relatively dry and the layers below that at field capacity. The wetting front reached 750mm within two hours after irrigation, 1050mm after 6 hours and 1200 after 12 hours, infiltration slowing down as the wetter deeper layers were reached. In the top 450mm layers maximum water contents were reached after only 2 hours. To a depth of 600mm field capacity was practically reached within 12 hours after irrigation. The latter seems to be true also for the 750mm layer, where a maximum water content was reached after 4 hours. With the exception of the layer at 1200mm, the water contents of the layers at 900mm and deeper showed small, gradual increases over a long period. At 1200 mm the water content reached a very high level, close to saturation, after 12 hours. Thereafter it declined slowly, but was still high even after 5 days. Air-filled porosity in this layer was clearly inadequate even at the latter stage. It appears that there must be a somewhat restricting layer just below 1200mm. It obviously also affected the water contents in the 1050mm (and to a lesser extent the 900mm) layers building up slowly over the 5 day period, to reach quite high values in the layer at 1050mm.

TABLE 5.6 - Soil water content at different soil depths at different times after irrigation at site ISO

Depth (mm)	Soil water content (%)								
	dry	2h	4h	12h	24h	2d	3d	4d	5d
150	15	40	32	31	31	31	31	31	30
300	13	35	34	32	32	32	32	32	31
450	13	33	31	31	31	31	31	31	31
600	15	30	30	30	30	32	32	32	32
750	17	31	34	33	33	33	33	33	32
900	21	26	29	29	30	32	32	32	32
1050	26	26	31	32	33	33	34	34	34
1200	33	33	33	37	36	35	35	35	35
1350	31	31	31	32	32	32	33	33	33
1500	32	32	32	33	33	33	33	33	33

In general it is clear that in the three soils without restricting layers close to the surface (D12, D16 and ISO) "field capacity" was for all practical purposes reached in the top layers within a few hours after irrigating an initially dry soil. At site ISO, where adequate water was applied, this was true to a soil depth of about 900mm. In an initially wet soil the situation is quite different, as was indicated by the results of the second irrigations at sites D12 and D16. Even in the latter cases the layers down to 600mm have already drained to field capacity by the time that the water contents in the layers below 750mm were still increasing towards field capacity.

From the above it is clear that it would be non-sensical to study field capacity and water uptake on a soil profile basis. It should be studied on a layer by layer basis in the wet range of plant available water. Furthermore, the good results obtained on the strongly layered soil at D6 and the widespread occurrence of such soils in many irrigated areas also warrants more study in the wet range in such soils. Hensley & De Jager (1982) and Boedt & Laker (1985) already expressed their concern regarding water uptake and plant performance in the "field capacity range" of water contents. It is strongly recommended that this aspect is studied in more detail - also in regard to stratified soils.

The importance of determining field capacity in the field is emphasized by the discrepancy between field determined values and those found at soil water potentials of -33kPa in the laboratory (Table 5.7). The soil water contents at a soil water potential of -33kPa were constantly lower than the values obtained in the field for sites D6, D12 and ISO. The use of the former values would, therefore, result in an underestimation of PAWC and destroy the purpose of the PAWC concept.

TABLE 5.7 - Volumetric water contents per horizon at different soil water potentials

Horizon	Water content (%)		
	-10kPa	-33kPa	-1500kPa
D6 A	24,1	18,7	8,9
D6 B	35,9	33,0	12,6
D6 C	27,7	22,2	10,1
D12 A	29,7	25,6	8,9
D12 B	28,7	22,4	7,9
D16	no data available		
ISO A	36,4	26,5	13,9
ISO B	28,6	23,1	11,1
ISO C	28,1	22,8	10,6

5.3.5 Rooting density

Rooting densities of maize were determined at site D6, D12 and D16 during the 1985-1986 season. The results are listed in Tables 5.8 and 5.9. The values clearly explain the water extraction patterns found in Chapter 3. The presence of the restricting layer at site D6 is clearly illustrated by the low rooting densities and low dry root mass below a depth of 900mm relative to the other sites. The deep extraction of soil water by maize at site D16 (see Chapter 3) is explained by the high rooting densities and high dry root mass throughout the soil profile, and especially in the deeper soil layers.

TABLE 5.8 - Rooting densities of maize at different soil depths at sites D6, D12 and D16 (sampled on 29/1/1986)

Depth (mm)	Density (cm per cubic cm)				
	D6b	D6c	D12b	D12c	D16b
0- 300	1,5150	1,7884	0,8329	1,3271	0,9240
300- 600	0,3974	0,3727	0,2685	0,3539	0,5113
600- 900	0,1981	0,1522	0,3266	0,2489	0,2828
900-1200		0,0873	0,1515	0,6220	0,6526
1200-1500				0,2601	0,6343

TABLE 5.9 - Dry root mass of maize at different soil depths at sites D6, D12 and D16 (sampled on 29/1/1986)

Depth (mm)	Dry mass (g)				
	D6b	D6c	D12b	D12c	D16b
0- 300	0,2316	0,2556	0,1785	0,0811	0,1166
300- 600	0,0355	0,0471	0,0631	0,0509	0,0690
600- 900	0,0171	0,0172	0,0230	0,0849	0,0512
900-1200		0,0035	0,0230	0,0849	0,0512
1200-1500				0,0324	0,0808
total	0,2842	0,3234	0,3306	0,3121	0,3543

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The "plant available water capacity" (PAWC) concept was developed by Hensley & De Jager (1982). The purpose of the PAWC concept was to define a well-founded and scientifically correct criterion which could accurately express the amount of water available to the plant. This would be very useful in irrigation scheduling as a tool to improve on water use efficiencies without significant reductions in yield. Hensley & De Jager (1982) obtained very interesting results in their research but could not test the PAWC concept by means of extensive irrigation scheduling experiments.

The PAWC concept was intensively studied by Boedt & Laker (1985) in order to supplement the work of Hensley & De Jager (1982). Boedt & Laker (1985) determined PAWC of certain crops on a variety of soils. The similarity of the results obtained by Hensley & De Jager (1982) to those obtained by Boedt & Laker (1985) on similar sites proved that the PAWC concept was a reliable criterion. It also proved that the PAWC concept yielded reproducible results as similar values were found by different researchers.

Laker (1982) used data obtained by Hensley & De Jager (1982) to develop mathematical models to determine PAWC on untested sites. The study of and further research on these mathematical models was done by Boedt & Laker (1985). The results of this study were very promising as predicted and field-determined values were very close.

The PAWC concept was extensively tested by Boedt & Laker (1985) by means of comparative irrigation scheduling experiments. They proved that the PAWC concept was a reliable criterion for irrigation scheduling. The PAWC concept was also tested by Bennie and his co-workers at the U.O.F.S. who, meanwhile, applied it in an excellent micro-computer programme for irrigation scheduling.

6.2 CONCLUSIONS

During the present study PAWC was determined during vegetative growth stages in order to study the development of the PAWC values as the plants near maturity. The results indicated that water stress during the vegetative stages possibly stimulates root development and, consequently, higher PAWC values were found during young growth stages than would be expected.

Pre-dawn leaf water potential and plant performance related parameters, such as stem elongation and leaf expansion, clearly indicated FMS during young growth stages in wheat, durum wheat and maize. During the early growth stages FMS was clearly identified when PLWP decreased to about -800kPa. During later stages FMS is indicated only by PLWP values of clearly less than -1000kPa, as was also found by Boedt & Laker (1985). It was found that stem elongation of maize plants was more sensitive than leaf expansion to water stress during the vegetative growth stages.

During the experiments with durum wheat it was found that the PLWP of immature leaves was constantly lower than that of mature leaves. This emphasizes the importance of a standardized method for PLWP measurements even to the point of choosing the leaf. It is, therefore, recommended to choose the youngest mature leaf of the plant. This was also suggested by Boedt & Laker (1985).

Plant physiological responses to water stress indicated that NCER was a more sensitive parameter to indicate FMS than pre-dawn leaf water potential, especially under climatic conditions characterized by a high evaporative demand. However, these conclusions are based on single, daily PLWP measurements. It is very important to realize that, when using PLWP as an indicator of FMS, trends in PLWP must be determined over an extended period, starting as soon as possible after irrigation.

The behaviour of plants under water stress conditions at different growth stages and the effects on vegetative growth and yield was also studied. The results indicated that water stress during the vegetative stages in wheat and maize did not necessarily result in lower yields, although vegetative growth was markedly affected. For durum wheat, yield was severely affected by water stress during young growth stages.

The PAWC concept was tested by means of extensive comparative irrigation scheduling experiments with wheat, durum wheat and maize as crops. These can be divided into three groups: Firstly, the determination of the fraction of PAWC that can be extracted before yields are significantly rèduced. Secondly, the application of deficit irrigation at extraction of different fractions of PAWC. Thirdly, the influence of soil water stress at different growth stages on yield and water use efficiencies for wheat and maize.

PAWC, defined as the amount of extractable water between FC and FMS and based upon identification of FMS by means of PLWP measurements, proved to be a reliable parameter for use in the design of irrigation scheduling strategies for maize. Yields were not reduced significantly even at extraction of 100% of PAWC. This is in contrast to the results of Boedt & Laker (1985), who found considerable maize yield losses at extraction of 100% PAWC. They concluded that it was not wise for maize to extract more than 71,5% of PAWC before applying the next irrigation. The overestimation of PAWC for maize was explained by the inaccuracy of PLWP as a parameter for identification of FMS under climatic conditions of extremely high evaporative demand (Boedt & Laker, 1985).

In the case of wheat extraction of 100% of PAWC again, as in the case of maize, did not reduce yields. This agrees with the results of Boedt & Laker (1985) for wheat and confirms the validity of PAWC, based upon FMS determined by means of PLWP measurements, as a parameter for irrigation scheduling for wheat.

Deficit irrigation failed to improve water use efficiencies based upon total water consumption (WUEt) for both maize and wheat. However, water use efficiencies based upon applied water (WUEi) were generally improved significantly by deficit irrigation practices. There was a clear tendency for high frequency deficit irrigation to give the best results in this regard. High frequency deficit irrigation around FMS (100% extraction of PAWC) gave better results than high frequency deficit irrigation combined with mild water extraction. The practical and economical implications of these findings are outlined in Section 6.3.

For both maize and wheat moderate water stress (extraction of 100% of PAWC) did not reduce yields at any growth stage. During the late vegetative stages even severe water stress (125% of PAWC extracted) did not reduce yields. Severe water stress at the flowering and grain filling stages reduced yields in both crops, although the reductions were not always statistically significant. The reductions during the grain filling stages were particularly severe.

During the irrigation scheduling experiments a study was done on the combined effects of the amount of soluble salts in the soil profile and the amounts of water applied at each irrigation. The results of this study indicated that the degree of salinity must be taken into account when determining the amounts of water to be applied at each irrigation. High frequency deficit irrigation combined with a high degree of salinity had a detrimental effect on yield while low frequency deficit irrigation treatments which involve applications of large amounts of water were more effective at the same degree of salinity.

6.3 PRACTICAL APPLICATION OF THE RESULTS OF THE PRESENT STUDY AND PREVIOUS PAWC RESEARCH

Laker (1985) pointed out that the most useful application of a knowledge of the PAWC of a certain soil for a certain crop probably lies in the fact that it facilitates reduction of the peak irrigation design without causing crop losses due to water stress during peak demand periods. This could effect a considerable saving on irrigation system costs. What is required for successful application of this concept is a correct knowledge of the PAWC of a specific soil-crop-atmosphere combination and the application of a suitable deficit irrigation strategy (i.e. where the soil is not filled to field capacity each time).

The present study clearly proved that deficit irrigation can be applied successfully during peak demand periods without reducing yields or irrigation water use efficiencies. In fact, deficit irrigation generally gave higher irrigation water use efficiencies than full irrigations.

Bennie and his co-workers at the U.O.F.S. have meanwhile developed an excellent model for reducing peak design criteria and irrigation scheduling during peak demand periods, making use of PAWC and deficit irrigation principles. In this approach the peak period is started on a full profile (at field capacity) and the PAWC is progressively exploited so that "first material stress" (the lower limit of PAWC) is reached at the end of the peak period. During this period a "frequent deficit" irrigation approach is applied. In other words, water application is less than crop demand, giving a progressive decline in soil water content from field capacity to first material stress. This model has been developed into the "hands-on" BEWAB micro-computer programme for irrigation scheduling (A.T.P. Bennie, U.O.F.S., Personal Communication).

The fact that deficit irrigations at soil water contents close to first material stress had no harmful effects on yield and water use efficiencies is ample proof that the above strategy for exploiting PAWC until first material stress (or a value close to it) is reached, is indeed a feasible irrigation management model.

6.4 RECOMMENDATIONS

6.4.1 Research

Pre-dawn leaf water potential measurements for determination of first material stress must follow a standardized procedure up to the point of leaf selection. The procedure described in Chapter 2 proved to be very reliable and gave highly reproducible results.

It is also recommendable to use the technique described by Reginato & Nakayama (1987) for taking standard counts with neutron hydroprobes in order to determine soil water contents. Standard counts are taken with the neutron probe mounted on a tube at about 1.5 meter above ground level, resulting in more consistent readings.

Intensive studies on the effects of water stress during young growth stages on root development are required. The PAWC values only gave an indirect assessment of the root development. Direct root growth monitoring will indicate how and where in the profile root growth is increased as a result of water stress. These experiments could easily be done in laboratories by using soil columns.

Detailed studies on soil water uptake by means of a highly accurate soil water content measuring apparatus could lead to some interesting results. This type of research will indicate from which parts of the profile water is extracted at different degrees of soil water content, ranging from field capacity to first material stress. It can also help to explain certain phenomena, such as the fluctuating phase in the pre-dawn leaf water potential patterns. These experiments should be done in laboratories and if possible in a controlled growth chamber in order to be able to measure the smallest variations in soil water content in any part of the profile and to have complete control of all external factors, such as temperature and humidity.

More research on the combined effects of salinity and the type of irrigation scheduling is required. These experiments can either be conducted in the field if saline soils are present or in laboratories where different degrees of salinity can be created in soil columns.

More research on deficit irrigation applications is recommended. More data on the effects of low and high frequency deficit irrigation, especially for wheat are required. This type of research should preferably be conducted in field trials as it involves the determination of yield and water use efficiencies.

6.4.2 Practical on-farm scheduling

Because the validity of the PAWC concept together with deficit irrigation scheduling has amply been proven and because water is the most important and simultaneously the limiting factor for agriculture in South Africa, the following recommendation can be put forward: Extension officers who are the main link for transfer of knowledge to the farmers, should make it their task to promote the PAWC concept and its use in practical irrigation scheduling. This can be done by the creation of technical centra which could determine PAWC of specific crops on specific soils all over the country. The results would then be used to establish irrigation scheduling programmes for each crop and for each soil or region while also taking into consideration the technical possibilities of the farms in question. Bennie and his co-workers at the U.O.F.S. have set an excellent example in this regard. Agricultural research stations could make it their task to prepare the farmers mentally by applying the PAWC concept in field trials and present the results to the farmers during organized meetings.

In view of the results obtained during the irrigation scheduling experiments the following conclusions and recommendations can be given:

1. Extending intervals between irrigations will improve water use efficiencies and save considerable amounts of water and capital. However, soil water extraction should not exceed 100% of PAWC (for the specific crop and soil) as this would reduce yields to economically unacceptable levels.

2. Deficit irrigation, in particular high frequency deficit irrigation around FMS for maize, will improve water use efficiencies without the risk of inducing water stress. This, again, means a considerable saving of water and capital input but with a lower risk of yield reductions.

3. If water supply is severely limited and crops will inevitably experience water stress at some stage during the growing season, then irrigations could be postponed during vegetative stages in order to save water and ensure an adequate amount of water in the soil profile during flowering and grain filling stages (moderate water stress during part of the latter is acceptable but not recommended).

REFERENCES

ACEVEDO, E., T.C. HSIAO & D.W. HENDERSON, 1971. Immediate and subsequent growth responses of maize leaves to changes in water status. Plant Physiol. 48, 631-636.

ALLERUP, S., 1961. Stem cutting and water movement in young barley plants. Physiol. Pl. 14, 632-637.

ALLMARAS, R.R., W.W. NELSON & W.B. VOORHIES, 1975. Soybean and corn rooting in South Western Minnesota: II. Root distributions and related water inflow. Soil Sci. Soc. Am. Proc. 39, 771-777.

ARNON, I., 1972. Crop Production in dry regions. Vol. I: Background and Principles. London SW1: Int. Textbook Company Ltd.

ARYA, L.M., G.R. BLAKE & D.A. FARRELL, 1975. A field study of soil water depletion patterns in presence of growing soybean roots: III. Rooting characteristics and root extraction of soil water. Soil Sci. Soc. Am. Proc. 39, 437-444.

ASPINALL, D., P.B. NICHOLLS & L.H. MAY, 1964. The effects of soil moisture stress on the growth of barley. I. Negative development and grain yield. Aust. J. Agric. Res. 15, 729-745.

BALDY, P., 1986. Comparison between growth chamber and field-grown Zea mays plants for photosynthetic carboxylase activities and other physiological characteristics with respect to leaf position. J. Exp. Bot. 37, 309-314.

BARLEY, K.P., 1963. Influence of soil strength on growth of roots. Soil Sci. 96, 175-180.

BARLEY, K.P. & E.L. GREACEN, 1967. Mechanical resistance as a soil factor influencing the growth of roots and underground shoots. Adv. Agron. 19, 1-43.

BARRS, H.D., 1968. Effect of cyclic variations in gas exchange under constant environmental conditions on the ratio of transpiration to net photosynthesis. Physiol. Pl. 21, 918-929.

BATES, L.M. & A.E. HALL, 1981. Stomatal closure with soil water depletion not associated with changes in bulk leaf water status. Oecologia 50, 62-65.

BEGG, J.E. & N.C. TURNER, 1976. Crop water deficits. Adv. Agron. J. 76, 829-835.

BENNET, J.M., J.W. JONES, B. ZUR & L.C. HAMMOND, 1986. Interactive effects of nitrogen and water stresses on water relations of field grown corn leaves. Agron. J. 78, 273-280.

BENNIE, A.T.P. & F.J.P. BOTHA, 1986. Effect of deep tillage and controlled traffic on root growth, water-use efficiency and yield of irrigated maize and wheat. Soil Tillage Res. 7, 85-95.

BENNIE, A.T.P. & R. du T. BURGER, 1979. Grondverdigting onder besproeiing op die Vaalhartsbesproeiingsskema. Vol. II. Die invloed van grondverdigting op die grond-plant sisteem. Verslag Nr. 79/2. Dept. of Soil Science, Univ. of the Orange Free State, Bloemfontein.

BIERHUYZEN, J.F. & R.O. SLATYER, 1964. Photosynthesis of cotton leaves under a range of environmental conditions in relation to internal and external diffusive resistances. Aust. J. Biol. Sci. 17,348-359.

BLACKMAN, P.G. & W.J. DAVIES, 1985. Root to shoot communication in maize plants of the effects of soil drying. J. Exp. Bot. 36, 39-48.

BOEDT, L.J.J. & M.C. LAKER, 1985. The development of profile available water capacity models. Alice: University of Fort Hare.

BOTHA, F.J.P. & A.T.P. BENNIE, 1983. Water uptake by maize and wheat: II. Critical evaluation of soil-root contact resistance. Paper presented at the 11th national congress of the Soil Science Society of South Africa, Stellenbosch.

BOTHA, F.J.P., A.T.P. BENNIE & R. du T. BURGER, 1983. Water use efficiency of irrigated crops as influenced by varying cultivation practices and root configurations. Report to the W.R.C., Pretoria.

BOYER, J.S., 1965. Effects of osmotic water stress on metabolic rates of cotton plants with open stomata. Plant Physiol. 40, 229-234.

BOYER, J.S., 1968. Relationship of water potential to growth of leaves. Plant Physiol. 43, 1056-1062.

BOYER, J.S. & H.G. McPHERSON, 1975. Physiology of water deficits in cereal crops. Adv. Agron. 27, 1-23.

BRIX, H., 1962. The effect of water stress on the rates of photosynthesis and respiration in tomato plant and loblolly pine seedlings. Physiol. Pl. 15, 10-20.

BUCHEIM, J.F. & L.F. PLOSS, 1977.Computerized irrigation scheduling using neutron probes. St. Joseph, Michigan: ASAE.

CAMP, C.R. & Z.E. LUND, 1964. Effect of soil compaction on cotton roots. Crop Soils 17(2), 13-14.

CANNELL, R.Q., 1969. The tillering pattern in barley varieties. I. Production, susvival and contribution to yield by component tillers. J. Agric. Sci. 72, 405-422.

CARBONNEAU, A., 1983. Measurement of gross photosynthesis under natural conditions by using a carbon(14)-dioxide diffusion porometer. 1. Description of some convenient techniques. Photosynthetica 17, 235-239.

CARTER. V.H. & S. CONWAY, undated. Predicting irrigation dates and amounts with a neutron moisture gauge. Denver: USBR.

CEULEMANS, R., I. IMPENS, M.C. LAKER, F.M.G. VANASSCHE & R. MOTTRAM, 1988a. Net CO2 exchange rate as a sensitive indicator of plant water status in corn (Zea mays L.). Can. J. Plant Sci. 68, 597-606.

CEULEMANS, R., F. KOCKELBERGH & I. IMPENS, 1986. A fast, low cost and low power requiring device for improving closed loop carbon-dioxide measuring systems. J. Exp. Bot. 37, 1234-1244.

CEULEMANS, R.J.M., M.C. LAKER & F.M.G. VANASSCHE, 1988b. Stomatal conductance and leaf temperature of maize grown under different irrigation treatments in a semi-arid region. Trop. Agric. (Trinidad) 65, 305-312.

CLASSEN, M.M. & R.H. SHAW, 1970. Water deficit effects on corn. II. Grain components. Agron. J. 62,652-655.

DAVIES, W.J., J. METCALF, T.A. LODGE & A.R. DA COSTA, 1986. Plant growth substances and the regulation of growth under drought. Aust. J. Plant Physiol. 13, 105-125.

DENMEAD, O.T. & R.H. SHAW, 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52, 272-274.

DOORENBOS, J. & A.H. KASSAM, 1979. Yield response to water. F.A.O. Irrigation and drainage paper No. 33. Rome: F.A.O.

DU PREEZ, C.C., A.T.P. BENNIE & R. DU.T. BURGER, 1979. Grondverdigting onder besproeiing op die Vaalhartsbesproeiingskema. III Die oorsake en bekamping van verdigting van sanderige besproeiingsgrond. Dept. van Grondkunde. Verslag No. 79/3. Univ. Oranje-Vrystaat, Bloemfontein.

DWYER, L.M. & D.W. STEWART, 1984. Indications of water stress in corn (Zea mays L.). Can. J. Plant Sci. 64, 537-546.

DWYER, L.M. & D.W. STEWART, 1985. Water extraction patterns and development of plant water deficits in corn. Can. J. Plant Sci. 65, 921-933.

DWYER, L.M. & D.W. STEWART, 1986. Effect of leaf age and position on net photosynthetic rates in maize (Zea mays L.). Agric. Forest Meteorol. 37, 29-46.

EASTHAM, J., D.M. OOSTERHUIS & S. WALKER, 1984. Leaf water and turgor potential threshold values for leaf growth of wheat. Agron. J. 76, 841-847.

ECK, H.V., 1986. Effects of water deficits on yield, yield components, and water use efficiency of irrigated corn. Agron. J. 78, 1035-1040.

EHLERS, W., B.K. KHOSLA, U. KOPKE, R. STULPNAGEL, W. BOHM & K. BAEUMER, 1980. Tillage effects on root development, water uptake and growth of oats. Soil Tillage Res. 1, 19-34.

EHLIG, C.F. & W.R. GARDNER, 1964. Relationship between transpiration and the internal water relations of plants. Agron. J. 56, 127-130.

ENGLISH, M.J. & B.C. NAKAMURA, 1982. Deficit irrigation: Effects of irrigation frequency on crop yield, 162-172. In: The Irrigation Association. 1982 Technical Conference Proceedings. "Water, Energy and Economic Alternatives".

ERICKSON, R.O., 1976. Modelling of plant growth. Ann. Rev. Plant Physiol. 27, 407-434.

EVANS, L.T., 1975. The physiological basis of crop yield. In: Crop physiology, pp. 327-335. Cambridge: Univ. Press.

FISCHER, R.A., 1973. The effects of water stress at various stages of development on yield processes in wheat. pp. 233-241. In R.O. Slatyer (ed.). Plant responses to climatic factors. Proc. Uppsala Symp., Uppsala, Sweden. 15-20 Sept. 1970. Unesco, Paris.

FREY, N.M., 1982. Dry matter accumulation in kernels of maize. Crop Sci. 21, 118-122.

GARDNER, W.R., 1983. Soil properties and efficient water use: an overview, 45-63. In: Limitations to efficient water use in crop production. Madison: ASA.

GARDNER, W.R. & R.H. NIEMAN, 1964. Lower limit of water available to plants. Science 143, 1460-1462.

GERWITZ, A. & E.R. PAGE, 1974. An empirical mathematical model to describe plant root systems. J. App. Ecol. 11(2), 773-771.

GOLLAN, T., J.B. PASSIOURA & R. MUNNS, 1986. Soil water status affects the stomatal conductance of fully turgid wheat and sunflower leaves. Aust. J. Plant Physiol. 13, 459-464.

GREACEN, E.L. & J.S. OH, 1972. Physics of root growth. Nature (London) New Biol. 235, 24-25.

GREEN, G.C., 1982. Progress report for 1981-1982 on the research project titled: "Evaporation and water use studies by means of weighing lysimeters: determination of water requirements of certain annual crops at Roodeplaat as a function of soil, plant and atmospheric factors." Dept. of Agriculture Pretoria: SIRI.

GREENFIELD, S.S., 1942. Inhibitory effects of inorganoc compounds on photosynthesis in Chlorella. Am. J. Bot. 29, 121-131.

HANKS, R.J., 1982. Predicting crop production as related to drought stress under irrigation. Logan: Utah State Univ.

HANKS, R.J. & V.P. RASMUSSEN, 1982. Predicting crop production as related to plant water stress. Adv. Agron. 35, 193-215.

HANWAY, J.J., 1966. How a corn plant develops. Iowa Coop. Ext. Serv. Spec. Rep. 48.

HENSLEY, M., 1984. The determination of profile available water capacities of soils. Ph.D. dissertation. Bloemfontein: University of the Orange Free State.

HENSLEY, M. & J.M. DE.JAGER, 1982. The determination of the profile available water capacities of soils. Alice: University of Fort Hare.

HILLEL, D., 1980. Applications of soil physics. New York: Academic Press.

HOFFMAN, G.J., S.L. RAWLINS, M.J. GARBER & E.M. CULLEN, 1971. Water relations and growth of cotton as influenced by salinity and relative humidity. Agron. J. 63, 822-826.

HOOGENBOOM, G., C.M. PETERSON & M.G. HUCK, 1987. Shoot growth rate of soybean as affected by drought stress. Agron. J. 79, 598-607.

HOOGENBOOM, G., M.G. HUCK & C.M. PETERSON, 1987. Root growth rate of soybean as affected by drought stress. Agron. J. 79, 607-614.

HSIAO, T.C., 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24, 519-570.

HSIAO, T.C., 1982. The Soil-Plant-Atmosphere Continuum in Relation to Drought and Crop Production. pp 39-52. In: Drought resistance in crops, with emphasis on rice. Los Banos: IRRI.

HSIAO, T.C., E. ACEVEDO & D.W. HENDERSON, 1970. Maize leaf elongation: continuous measurement and close dependence on plant water status. Science 168, 590-591.

HSIAO, T.C., E. FERERES, E. ACEVEDO & D.W. HENDERSON, 1976. Water stress and dynamics of growth and yield of crop plants. In: Water and plant life: Problems and modern approaches, pp. 281-305. Springer-Verlag, Berlin, Heidelberg, New York.

HSIAO, T.C., J.C. O'TOOLE & V.S. TOMAR, 1980. Water stress as a constraint to crop production in the tropics. pp. 339-369. In: Priorities for aleviating Soil-Related Constraints Food Production in the Tropics. Los Banos; IRRI.

HUCK, M.G., 1977. Root distribution and water uptake patterns. In: The Belowground Ecosystem: A synthesis of Plant-Associated Processes. Ed. J.K. Marshall. Colorado State Univ., Colorado.

HUCK, M.G., K. ISHIHARA, C.M. PETERSON & T. USHIJIMA, 1983. Soybean adaptation to water stress at selected stages of growth. Plant Physiol. 73, 422-427.

HUMAN, J.J. & L.P. DE BRUYN, 1988. Final report to the Water Research Commission: Die invloed van verskillende tye en intensiteite van plantwaterstremming op fotosintese van sekere akkergewasse. Dept. Agronomie en Hortologie: UOVS.

IDSO, S.B., R.D. JACKSON, P.J. PINTER, R.J. REGINATO & J.L. HATFIELD, 1981. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteorol. 24, 45-55.

JACKSON, R.D., S.B. IDSO, R.J. REGINATO & P.J. PINTER, Jr., 1981. Canopy temperature as a crop water stress indicator. Water Resources Research 17, 1133-1138.

JONES, H.G. & E.J.M. KIRBY, 1977. Effects of manipulation of number of tillers and water supply on grain yield in barley. J. Agric. Sci. 88, 391-397.

KIRBY, E.J.M. & H.G. JONES, 1977. The relations between the main shoot and tillers in barley. J. Agric. Sci. 88, 381-389.

KLEPPER, B., 1983. Managing root systems for efficient water uses: Axial resistances to flow in root systems - Anatomical considerations. 115-124. In: Limitations to efficient water use in crop production. Taylor, H.M., R.J. Wayne & T.R. Sinclair (Ed). Madison U.S.A. : Am. Soc. of Agronomy, Inc., Crop Sci. of Am., Inc., Soil Sci. Soc. of Am., Inc.

KLEPPER, B., R.W. RICKMAN & C.M. PETERSON, 1982. Quantitative characterization of seedling development in small cereal grains. Agron. J. 74, 789-792.

KRAMER, P.J., 1969. Plant and soil water relationships: A modern synthesis. McGraw-Hill, New York.

LAKER. M.C., 1982. A provisional simple model for predicting PAWC for maize on certain Ciskeian soils. In: The determination of the profile available water capacities of soils, by Hensley and De Jager. Alice: University of Fort Hare.

LAKER, M.C., 1983. Report on a study tour to Belgium, the Netherlands and the United States of America. Alice: University of Fort Hare.

LAKER, M.C., 1985. Reducing peak water requirement by using soil water capacities. Paper presented at SABI Congress '85, Christiana.

LAKER, M.C., R.J.M. CEULEMANS & F.M.G. VANASSCHE, 1988. Effects of soil water stress on stomatal diffusion conductance and leaf water potential in maize at flowering stage. Unpublished, Appendix 3.4.

LANG, A. & M.R. THORPE, 1986. Water potential, translocation and assimilate partitioning. J. Exp. Bot. 37, 495-503.

LARCHER, W., 1980. Physiological plant ecology. New York: Springer.

LARGE, E.C., 1954. Growth stages in cereals. Illustration of the Feekes Scale. Plant Pathol. 3, 128-129.

LAWLOR, D.W., W. DAY, A.E. JOHNSON, B.J. LEGG & K.J. PARKINSON, 1981. Growth of spring barley under drought: Crop development, photosynthesis, dry matter accumulation and nutrient content. J. Agric. Sci. 96, 167-186.

LORENS, G.F., J.M. BENNETT & L.B. LOGGALE, 1987. Differences in drought resistance between two corn hybrids. I. Water relations and root length density. Agron. J. 79, 802-807.

LOWRY, F.E., H.M. TAYLOR & M.G. HUCK, 1970. Growth rate and yield of cotton as influence by depth and bulk density of soil. Soil Sci. Soc. Am. Proc. 34, 306-309.

MACVICAR, C.N., J.M. DE VILLIERS, R.F. LOXTON, E. VERSTER, J.J.N. LAMBRECHTS. F.R. MERRYWEATHER, J. LE ROUX, T.H. VAN ROOYEN & H.J. von M. HARMSE, 1977. Soil Classification. A Binomial System for South Africa. Pretoria: Dept. of Agriculture.

MALLETT, J.B., 1972. The use of climatic data for maize grain yield predictions. Ph.D. thesis, University of Natal.

MALLETT, J.B. & J.M. DE JAGER, 1971. Effect of a moisture stress day upon maize performance. Agroplantae 3, 15-20.

MEIDNER. H., 1965. Stomatal control of transpirational water loss. Symp. Soc. Exp. Biol. 19, 185-203.

MEYER, W.S. & G.C. GREEN, 1980. Water use by wheat and plant indicators of available soil water. Agron. J. 72, 253-257.

MEYER, W.S. & G.C. GREEN, 1981. Plant indicators of wheat and soybean crop water stress. Irrig. Sci. 2, 167-176.

MILLER, D.E., 1977. Deficit high frequency irrigation of sugarbeets, wheat and beans. Proc. Speciality Conf. on Water, Irrigation and Management for Drainage. New York: ASCE.

MULLER, H.L., 1988. Die verwantskap tussen plantspasiering, wortelverspreiding en wateronttrekking by mielies in 'n grond van die Bleeksandserie. Unpublished M.Sc. Agric. thesis. Univ. of the Orange Free State, Bloemfontein.

NEALES, T.F. & L.D. INCOLL, 1968. The control of leaf photosynthesis rate by the level of assimilate concentration in the leaf: A review of a hypothesis. Bot. Rev. 34, 107-125.

OOSTERHUIS, D.M. & P.M. CARTWRIGHT, 1983. Spike differentiation and floret survival in semidwarf spring wheat as affected by water stress and photoperiod. Crop Sci. 23, 711-717.

ORDIN, L., 1958. The effect of water stress on the cell wall metabolism of plant tissue. In: Radio-isotopes in scientific research. Vol. 4, pp. 553-564. Pergamon Press, New York.

ORDIN, L., 1960. Effect of water stress on cell metabolism of Avena coleoptile tissue. Plant Physiol. 35, 443-450.

PAYNE, D., 1973. Soil mechanical properties and root growth. J. Sci. Food Agr. 25, 235.

PHILIP, J.R., 1957. Evaporation and moisture and heat fields in the soil. J. Meteor. 14, 354-366.

RAMSEUR, E.L., S.U. WALLACE & V.L. QUISENBERRY, 1985. Growth of "Braxton" soybeans as influenced by irrigation and intrarow spacing. Agron. J. 77, 163-168.

RATLIFF, L.F., J.T. RITCHIE & D.K. CASSEL. 1983. Field measured limits of soil water availability as related to laboratory-measured properties. Soil Sci. Soc. Am. J. 47, 770-775.

REGINATO, R.J. & F.S. NAKAYAMA, 1987. Plastic standards for transferring neutron probe calibrations. Proc. Int. Symp. on Measurement of Soil and Plant Water Status, Vol. 1, 17-20. Logan: USA.

RICHARDS, L.A. & L.R. WEAVER, 1944. Moisture retention by some irrigated soils as related to soil moisture tension. J. Agr. Res. 69, 215-235.

RICKMAN. R.W., B.L. KLEPPER & C.M. PETERSON, 1983. Time distributions for describing appearance of specific culms of winter wheat. Agron. J. 75, 551-556.

RITCHIE, J.T., 1981. Soil water availability. Plant and soil 58, 327-338.

ROBINS. J.S. & C.E. DOMINGO, 1953. Some effects of severe soil moisture deficits at specific growth stages in corn. Agron. J. 45, 618-621.

ROSENTHAL, W.D., G.F. ARKIN, P.J. SHOUSE & W.R. JORDAN, 1987. Water deficit effects on transpiration and leaf growth. Agron. J. 79,1019-1026.

SCHOLANDER, P.F., H.T. HAMMEL, E.A. HEMMINGSEN & E.D. BRADSTREET, 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. Pro. Nat. Acad. Sci. U.S.A. 52, 119-125.

SHAW, J.S., 1974. A weighted moisture-stress index for corn in Iowa. Iowa State J. Res. 49, 101-114.

SHIERLAW, J. & A.M. ALSTON, 1984. Effect of soil compaction on root growth and uptake of phosphorus. Plant Soil 77, 15-28.

SINGH, T. & D.S. MALIK, 1983. Effect of water stress at three growth stages on the yield and water-use efficiency of dwarf wheat. Irr. Sci. 4, 239-245.

SKAGGS, R.W., D.E. MILLER & R.H. BROOKS, 1982. Soil water, part 1: properties, 77-123. In: Design and operation of farm irrigation systems. St. Joseph, Michigan: ASAE.

SLATYER, R.O., 1967. Plant-water relationships. Academic Press Inc., New York.

SLATYER, R.O., 1973. The effect of internal water status on plant growth, development and yield. pp. 177-191. In R.O. Slatyer (ed.). Plant responses to climatic factors. Proc. Uppsala Symp., Uppsala, Sweden. 15-20 Sept. 1970. Unesco, Paris.

STALFELT, M.G., 1961. The effect of the water deficit on the stomatal movements in a cabon-dioxide free atmosphere. Physiol. Pl. 14. 826-843.

STARK. J.C. & T.S. LONGLEY, 1986. Changes in spring wheat tillering patterns in response to delayed irrigation. Agron. J. 78, 892-896.

STEEL, R.G.D. & J.H. TORRIE, 1980. Principles and Procedures of Statistics: A Biometrical Approach. New York: McGraw-Hill Inc.

STICKLER, F.C., S. WEARDEN & A.W. PAULI, 1961. Leaf area determination in grain sorghum. Agron. J. 53, 187-188.

STOKER, D.J., 1977. Statistical tables. Pretoria: Academica.

TAYLOR, H.M. & H.R. GARDNER, 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. Soil Sci. 96, 153-156.

TAYLOR, H.M. & B. KLEPPER, 1978. The role of rooting characteristics in the supply of water to plants. Adv. Agron. 30. 99-128.

TAYLOR, H.M., G.M. ROBERSON & J.J. PARKER, 1966. Soil strength-root penetration relationship for medium to coarse-textured soil materials. Soil Sci. 102, 18-22.

TAYLOR, H.M. & L.F. RATLIFF, 1969. Root elongation rates of cotton and peanuts as a function of soil strength and water content. Soil Sci. 108, 113-119.

THORNE, J.H. & R.H. KOLLER, 1974. Influences of assimilate demand on photosynthesis, diffusive resistances, translocation, and carbohydrate levels of soybean leaves. Plant Physiol. 54, 201-207.

THORNTHWAITE, C.W., 1948. An approach toward a rational classification of climate. Geog. Rev. 38 (1), 55-94.

THORNTHWAITE, C.W. & J.R. MATHER, 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Drexel Inst. Techn. Lab. of Climatology. Publ. in Climatology 10: 311pp.

TOLLENAAR, M., 1977. Sink-source relationships during reproductive development in maize. A review. Maydica XXII, 49-75.

TURNER, N.C., E.D. SCHULZE & T. GOLLAN, 1985. The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content. II. In the mesophytic herbaceous species Helianthus annuus. Oecologia 65, 348-355.

VAN ANTWERPEN, R., 1988. Evaluasie van verskillende empiriese modelle vir die voorspelling van wortelgroei. M.SC. Agric. thesis Univ. of Orange Free State.

VAN HUYSSTEEN, L. & J.L. VAN ZYL, 1981. Effects of soil compaction on subsoil root penetration and shoot growth of wine grapes. Proc. of the 10th National Congress of the S.S.S. of S.A., Tech. Comm. No. 180. Dept. of Agriculture, Pretoria.

WENDA, W.I. & R.J. HANKS, 1981. Corn yield and evapotranspiration under simulated drought conditions. Irr. Sci. 2, 193-204.

APPENDICES

APPENDIX 2.1.1 PROFILE DESCRIPTION AND ANALYTICAL DATA FOR SITE D6

FORM:OAKLEAF
SERIES:LIMPOPO

A (0-470 mm): Dry; dull yellowish brown, 10YR 5/4 (dry); dark brown, 10YR 3/4 (moist); fine sandy loam; massive; hard when dry; roots; recent deposit; abrupt undulating boundary (450-650 mm).

IIBt (470-800 mm): Dry; brown, 7.5YR 4/4 (dry); brown, 7.5YR 4/3 (moist); loamy silt, clayish; weak medium angular blocky; clay coatings; calcareous material; slightly hard to hard; few fine roots; weakly permeable; buried horizon; clear boundary.

IIC (800-1500 mm): Wet; dull yellowish brown, 10YR 5/4 (moist); fine loamy sand; massive; very friable; calcareous spots; few fine roots.

Horizon	A	Bt	C
Particle size distribution (%)			
clay	7,0	26,4	15,2
fine silt	11,4	24,5	28,1
coarse silt	10,6	11,7	17,3
total silt	22.0	36,2	45,4
0.05-0.1mm	28.3	16,3	21,2
0,1-0,25mm	34,4	14,6	15,6
0,25-0.5mm	6,4	3,5	2,3
0,5-1,0 mm	1,3	0,8	0,4
1,0-2,0 mm	0,2	0,2	0,1
total sand	70,6	35,4	39,6
total	99,6	98,0	100,2
Exchangeable cations (me/100g soil)			
Ca	3,2	7,9	3,8
Mg	3,7	9,7	8,7
K	0,5	1,3	0.6
Na	0,4	0,9	1,4
C.E.C. (me/100g soil)	7,8	19.8	14,5

Soil Taxonomy: Mollic Ustifluvent

APPENDIX 2.1.2 PROFILE DESCRIPTION AND ANALYTICAL DATA FOR SITE D12

FORM: OAKLEAF
SERIES: LIMPOPO

Ap (0-350 mm): Dry: dull yellowish brown, 10YR 5/4 (dry); dark brown, 10YR 3/4 (moist); fine sandy loam; massive; hard when dry; roots; abrupt transition.

IIB1 (350-720 mm): Dry; dull yellowish brown, 10YR 5/3 (dry); dark brown, 10YR 3/4 (moist); fine silty loam; weak angular blocky; roots; presence of calcareous material; clear boundary.

IIBt (720-830 mm): Dry; dark reddish brown, 5YR 3/2 (dry); dark reddish brown, 5YR 3/4 (moist); fine silty loam, clayish; medium angular blocky; clay cutans; roots; presence of calcareous material; abrupt transition.

IIC (830-1500 mm): Wet; brown, 10YR 4/4 (moist); fine loamy sand; massive; very friable; few fine roots; spots of calcareous material.

Horizon	A	B1	B2t	C
Particle size distribution (%)				
clay	9,2	15,7	32,7	12,6
fine silt	10,6	17,1	18,6	20,1
coarse silt	11,6	11,8	9,5	17,1
total silt	22,2	28,9	28,1	37,2
0,05-0,1mm	30,6	24,9	17,8	35,0
0,1-0,25mm	31,4	26,3	17,9	14,0
0,25-0,5mm	5,7	4,0	2,7	0,7
0,5- 1,0mm	0,8	0,3	0,2	0,4
1,0- 2,0mm	0,1	0,0	0,2	0,2
total sand	68,6	55,5	38,8	50,3
total	100,0	100,1	99,6	100,1
Exchangeable cations (me/100g soil)				
Ca	4,0	5,2	11,3	4,2
Mg	3,5	6,5	10,6	7,4
K	0,7	0,3	0,4	0,4
Na	0,5	1,0	1,9	1,7
C.E.C. (me/100g soil)	8,7	13,0	24,2	13,6

Soil Taxonomy: Mollic Ustifluvent

APPENDIX 2.1.3 PROFILE DESCRIPTIONS AND ANALYTICAL DATA FOR SITE D16

FORM: DUNDEE
SERIES: DUNDEE

Ap (0-300 mm): Dry; dull yellowish brown, 10YR 5/4 (dry); dark brown, 10YR 3/4 (moist); fine sandy loam; massive; hard when dry; roots; abrupt transition.

IIC (300-1500 mm): Dry; dull yellowish brown, 10YR 5/3 (dry); dark brown, 10YR 3/4 (moist); fine silty loam; massive; occasional boulders with diameter from 10 to 200 mm; roots; presence of calcareous material.

Horizon	A	C
Particle size distribution (%)		
clay	20,4	15,1
fine silt	14,7	21,3
coarse silt	11,5	21,1
total silt	26,2	42,4
0,05-0,1mm	22,2	30,0
0,1-0,25mm	24,5	11,4
0,25-0,5mm	5,4	0,7
0,5- 1,0mm	0,7	0,3
1,0- 2,0mm	0,0	0,2
total sand	52,8	42,6
total	99,4	100,1
Exchangeable cations (me/100g soil)		
Ca	3,4	6,4
Mg	7,8	6,2
K	0,6	0,3
Na	2,5	0,5
C.E.C. (me/100g soil)	14,3	13,4

Soil Taxonomy: Mollic Ustifluvent

APPENDIX 2.1.4 PROFILE DESCRIPTION AND ANALYTICAL DATA FOR SITE ISO

FORM: Oakleaf
SERIES: Allanridge

A (0-230 mm): Dry; dull brown, 7.5YR 5/4 (dry); brown, 7.5YR 4/4 (moist); fine sandy loam; massive; hard when dry; roots; clear transition.

B1 (230-370 mm): Dry; dull brown, 7.5YR 5/4 (dry); brown, 7.5YR 4/4 (moist); fine sandy loam; very weak angular blocky; roots; abrupt transition.

IIB2 (370-770 mm): Dry; dull yellowish brown, 10YR 5/4 (dry); brown, 10YR 4/4 (moist); fine loamy silt; moderate, medium angular blocky; clay cutans; roots; spots of calcareous material; abrupt transition.

IIB3 (770-1220 mm): Wet; brown, 10YR 4/6 (moist); fine loamy sand; very weak angular blocky; few clay cutans; roots; spots of calcareous material; abrupt transition.

IIC (1220-1500 mm): Wet; brown, 7.5YR 4/6 (moist); fine loamy silt; massive; friable; spots of calcareous material.

Horizon	A	B1	B2t	B3	C
Particle size distribution (%)					
clay	17,2	9,1	9,3	6,8	14,8
fine silt	16,9	14,8	19,2	25,6	12,1
coarse silt	17,6	13,5	18,7	19,7	25,6
total silt	34,5	28,3	37,9	45,3	37,7
0,05-0,1mm	26,3	26,9	25,2	26,8	17,2
0,1-0,25mm	21,0	32,9	25,1	19,4	24,4
0,25-0,5mm	1,3	3,7	1,8	1,2	2,9
0,5- 1,0mm	0,1	0,1	0,2	0,1	0,5
1,0- 2,0mm	0,0	0,0	0,0	0,0	0,5
total sand	48,7	63,6	52,3	47,5	45,5
total	100,4	101,0	99,5	99,6	98,0
Exchangeable cations (me/100g soil)					
Ca	8,9	1,6	4,1	2,2	0,0
Mg	6,2	4,8	9,0	5,4	6,6
K	0,9	0,7	0,6	0,3	0,5
Na	0,6	2,5	1,3	4,3	13,8
C.E.C. (me/100g soil)	16,6	9,6	15,0	12,2	20,6

Soil Taxonomy: Typic Ustifluvent

APPENDIX 2.2.1 AGRONOMIC PRACTICES FOR THE 1985 WINTER SEASON AT SITES D6, D12, D16 AND ISO.

3/7/1985 Fertilizer application at sites D6, D12 and D16
150kg/ha superphosphate
200kg/ha ammoniumsulphate
Sowing of wheat and durum wheat at sites D6, D12 and D16
wheat cultivar: Zaragossa
durum wheat cultivar: Fargo
100kg seed per hectare
rows 150mm apart

4/7/1985 Fertilizer application at site ISO
250kg/ha superphosphate
200kg/ha ammoniumsulphate
Sowing of wheat and durum wheat at site ISO
wheat cultivar: Zaragossa
durum wheat cultivar: Fargo
100kg seed per hectare
rows 150mm apart

8/7/1985
9/7/1985 Fertilizer application at sites D6 and D12 (y.g. stages)
150kg/ha superphosphate
200kg/ha ammoniumsulphate
Sowing of wheat at sites D6 and D12 (young growth stages)
wheat cultivar: Zaragossa
100kg seed per hectare
rows 150mm apart

16/7/1985 Emergence at sites D6, D12, D16 and ISO

18/7/1985 Irrigation at sites D6, D12 and ISO

19/7/1985 Irrigation at site D16 and D6(y.g.)

21/7/1985 Irrigation at site D6(y.g.) and D12(y.g.)

13/8/1985 Fertilizer application at sites D6, D12, D16, ISO, D6(y.g.) and D12(y.g.)
200kg/ha ammoniumsulphate
Irrigation at sites D6, D12, D16, ISO, D6(y.g.) and D12(y.g.)
Start drying cycle on plots a at sites D6(y.g.) and D12(y.g.)

21/8/1985 Irrigation at sites D6(y.g.) and D12(y.g.): plots b, c and d

22/8/1985 Weed control treatment at all sites
4 liter MCPA per hectare at 1:100 dilution

27/8/1985 Irrigation at sites D6, D12 and D16

28/8/1985 Irrigation at site ISO

3/9/1985 Irrigation at sites D6(y.g.) and D12(y.g.): plots b, c and d
Start drying cycle on plots b at sites D6(y.g.) and D12(y.g.)

9/9/1985 Irrigation at sites D6 and D12

12/9/1985 Irrigation at site ISO
Irrigation at sites D6(y.g.) and D12(y.g.)
End drying cycle on plots a
Irrigation furrow collapsed: impossible to irrigate plots c and d

16/9/1985 Irrigation at sites D6(y.g.) and D12(y.g.): plots a (additional), c and d
Start drying cycle on plots c at sites D6(y.g.) and D12(y.g.)

23/9/1985 Irrigation at sites D6, D12 and D16
Irrigation at sites D6(y.g.) and D12(y.g.): plots a and d
Start drying cycle on plots d

24/9/1985 Irrigation at site ISO

2/10/1985 Irrigation at sites D6, D12 and D16

4/10/1985 Irrigation at site ISO

10/10/1985 Flowering at all sites (wheat)

11/10/1985 Irrigation at sites D6, D12, D16 and ISO
Start drying cycles for wheat at all sites

21/10/1985 Flowering at all sites (durum wheat)

23/10/1985 Irrigation at sites D6, D12, D16 and ISO
durum wheat plots
Start drying cycles for durum wheat at all sites

18/11/1985 Irrigation at sites D6, D12 and D16

19/11/1985 Irrigation at site ISO

APPENDIX 2.2.2 AGRONOMIC PRACTICES FOR THE 1985 WINTER SEASON AT SITE ISO (A-BLOK).

18/6/1985 Fertilizer application
250kg/ha superphosphate
200kg/ha ammoniumsulphate
Irrigation

3/7/1985 Sowing on plots 2 to 5 and 17 to 28
wheat cultivar: Zaragossa
100kg seed per hectare
rows 150mm apart

4/7/1985 Sowing on plots 1 and 6 to 16
wheat cultivar: Zaragossa
100kg seed per hectare
rows 150mm apart

5/7/1985 Sowing on plots 29 and 30
wheat cultivar: Zaragossa
100kg seed per hectare
rows 150mm apart

16/7/1985 Emergence on all plots

18/7/1985 Irrigation on all plots

15/8/1985 Fertilizer application
200kg/ha ammoniumsulphate
Irrigation on all plots

22/8/1985 Weed control treatment
4 liter MCPA per hectare at 1:100 dilution

28/8/1985 Irrigation on all plots

12/9/1985 Irrigation on all plots

24/9/1985 Irrigation on all plots

10/10/1985 Flowering

11/10/1985 Irrigation on all plots
Start experiments

10/12/1985 Harvest

APPENDIX 2.2.3 AGRONOMIC PRACTICES FOR THE 1985-1986 SUMMER EXPERIMENTS AT SITES D6, D12 AND D16.

Soil at field capacity before planting

29/10/1985	Fertilizer application at all sites 300kg/ha superphosphate 150kg/ha ammoniumsulphate
6/11/1985	Planting at all sites maize cultivar: Pioneer PNR 542 50000 plants per hectare rows 1m apart, plants 200mm apart
13/11/1985	Emergence
18/11/1985	Irrigation at all sites
9/11/1985	Thinning out
27/11/1985	Irrigation at all sites
2/12/1985	Fertilizer application at all sites 150kg/ha ammoniumsulphate
4/12/1985	Pest control treatment at all sites trichlorfon application
5/12/1985	Start drying cycle on plots a at all sites
17/12/1985	Fertilizer application on plots b, c, d and e 150kg/ha ammoniumsulphate Irrigation on plots b, c, d and e Start drying cycle on plots b
6/1/1986	Irrigation at sites D12 and D16: plots c, d and e Start drying cycle on plots c at sites D12 and D16
13/1/1986	Irrigation at site D6: plots c, d and e Start drying cycle on plot c at site D6
17/1/1986	Irrigation at sites D12 and D16: plots a, d and e Irrigation at site D6: plot a
24/1/1986	Irrigation at all sites: plots a, d and e Start drying cycle on plots d at all sites Flowering
29/1/1986	Collecting root samples on plots b and c at all sites (Prof. A.T.P. Bennie)
4/2/1986	Irrigation at all sites: plots a,b and e
11/2/1986	Irrigation at sites D6 and D12: plots a, b, c and e
12/2/1986	Irrigation at site D16: plots a, b, c and e
19/2/1986	Irrigation at site D6: plots a, b, c and e
21/2/1986	Irrigation at sites D12 and D16: plots a, b, c and e
3/3/1986	Irrigation at all sites: plots a, b, c, d and e
12/5/1986	Harvest

APPENDIX 2.2.4 AGRONOMIC PRACTICES FOR THE 1985-1986 SUMMER EXPERIMENTS AT SITE ISO (B-BLOK).

Soil at field capacity before planting

17/10/1985 Irrigation on all plots

18/10/1985 Irrigation on all plots

28/10/1985 Fertilizer application on all plots
300kg/ha superphosphate
150kg/ha ammoniumsulphate

29/10/1985 Planting on all plots
maize cultivar: Pioneer PNR 542
50000 plants per hectare
rows 1m apart, plants 200mm apart

9/11/1985 Emergence on all plots

14/11/1985 Irrigation on all plots

21/11/1985 Thinning out

2/12/1985 Fertilizer application on all plots
150kg/ha ammoniumsulphate

4/12/1985 Pest control treatment on all plots
trichlorfon application

18/12/1985 Fertilizer application on all plots
150kg/ha ammoniumsulphate
Irrigation on all plots

31/12/1985 Extra fertilizer application on plots 21 to 23, 26 and 27
100kg/ha ammoniumsulphatenitrate
Irrigation on all plots
Start of the experiments

16/1/1986 Flowering

9/5/1986 Harvest

APPENDIX 2.2.5 AGRONOMIC PRACTICES FOR THE 1986 WINTER SEASON AT SITES D6, D12 AND D16.

Soils at field capacity before planting

20/5/1986 Preparation of the plots at sites D6 and D12
Irrigation at sites D6 and D12
27/5/1986 Preparation of the plots at site D16
Irrigation at site D16
Levelling at sites D6 and D12
10/6/1986 Fertilizer application at sites D6, D12 and D16
3ton/ha gypsum
100kg/ha superphosphate
250kg/ha ammoniumsulphate
16/6/1986 Sowing wheat at site D6
wheat cultivar: Gamtoos
100kg seed per hectare
rows 300mm apart
18/6/1986 Sowing wheat at sites D12 and D16
wheat cultivar: Gamtoos
100kg seed per hectare
rows 300 mm apart
26/6/1986 Irrigation at sites D6, D12 and d16
29/6/1986 Emergence at site D6
29/6/1986 Emergence at sites D12 and D16
21/7/1986 Irrigation at all sites
30/7/1986 Irrigation at all sites
Start drying cycles on plots a at all sites
8/8/1986 Irrigation at all sites: plots b, c, d, and e
Start drying cycles on plots b at all sites
20/8/1986 Irrigation at all sites: plots c, d and e
Start drying cycles on plots c at all sites
29/8/1986 Irrigation at all sites: plots d and e
Start drying cycles on plots d at all sites
12/9/1986 Irrigation at all sites: plots a and e
19/9/1986 Irrigation at all sites: plots a, b and e
26/9/1986 Irrigation at all sites: plots c and d
7/10/1986 Fertilizer application at all sites
150kg/ha ammoniumsulphate
Irrigation at all sites
8/10/1986 Flowering
13/10/1986 Pest control treatment
650ml Parathion and 500ml Metasystox diluted in 200 liter water
Irrigation at site D6
14/10/1986 Irrigation at sites D12 and D16
23/10/1986 Irrigation at site D6
24/10/1986 Irrigation at sites D12 and D16
5/11/1985 Irrigation at all sites
24/11/1986 Harvest

APPENDIX 2.2.6 AGRONOMIC PRACTICES FOR THE 1986 WINTER SEASON AT SITE ISO (B-BLOK).

Soils at field capacity before planting

23/5/1986 Preparation of the plots
Irrigation on all plots

10/6/1986 Fertilizer application on all plots
4ton/ha gypsum
100kg/ha superphosphate
250kg/ha ammoniumsulphate

12/6/1986 Sowing wheat
cultivar: Gamtoos
100kg seed per hectare
rows 300mm apart

13/6/1986 Sowing durum wheat
cultivar: Moni
100kg seed per hectare
rows 300mm apart

23/6/1986 Irrigation on all plots

25/6/1986 Emergence of wheat
Light irrigation

26/6/1986 Emergence of durum wheat
Light irrigation

21/7/1986 Irrigation on all plots

8/8/1986 Irrigation on all plots

28/8/1986 Fertilizer application on all plots
150kg/ha ammoniumsulphate
Irrigation on all plots
all plots at field capacity
Start of the experiments

3/10/1986 Wheat at flowering stage

9/10/1986 Durum wheat at flowering stage

13/10/1986 Pest control treatment
650ml Parathion and 500ml Metasystox diluted in 300 liter water

1/12/1986 Harvest

APPENDIX 2.2.7 AGRONOMIC PRACTICES FOR THE 1986-1987 SUMMER SEASON AT SITES D6 AND D12.

Soils at field capacity before planting

13/10/1986 Fertilizer application at sites D6 and D12
3ton/ha gypsum
200kg/ha superphosphate
250kg/ha ammoniumsulphate
Irrigation on all plots

20/10/1986 Planting maize on all plots
cultivar: Pioneer PNR 542
40000 plants per hectare
rows 1m apart, plants 250mm apart

27/10/1986 Emergence on all plots
Light irrigation on all plots

5/11/1986 Irrigation on all plots

17/11/1986 Irrigation on all plots
Start drying cycle on plots a

27/11/1986 Irrigation at sites D6 and D12: plots b,c,d and e
Start drying cycle on plots b

5/12/1986 Irrigation at sites D6 and D12: plots e

8/12/1986 Irrigation at sites D6 and D12: plots c
Start drying cycle on plots c

10/12/1986 Irrigation at sites D6 and D12: plots d and e

19/12/1986 Irrigation at sites D6 and D12: plots d and e
Start drying cycle on plots d

29/12/1986 Irrigation at sites D6 and D12: plots e

6/1/1987 Irrigation on all plots

13/1/1987 Fertilizer application on all plots
150kg/ha ammoniumsulphate
Irrigation on all plots
Flowering

22/1/1987 Irrigation on all plots

2/2/1987 Irrigation on all plots

24/2/1987 Irrigation on all plots

29/5/1987 Harvest

APPENDIX 2.2.8 AGRONOMIC PRACTICES FOR THE 1986-1987 SUMMER SEASON AT SITE ISO (A-BLOK).

21/10/1986 Fertilizer application on all plots
3ton/ha gypsum
200kg/ha superphosphate
150kg/ha ammoniumsulphate

22/10/1986 Planting maize on all plots
cultivar: Pioneer PNR 542
40000 plants per hectare
rows 1m apart, plants 250mm apart

23/10/1986 Irrigation on all plots

1/11/1986 Emergence
Light irrigation to soften crust

7/11/1986 Irrigation on all plots

24/11/1986 Irrigation on all plots

4/12/1986 Fertilizer application on all plots
200kg/ha ammoniumsulphate
Irrigation on all plots

19/12/1986 Extra fertilizer application on plots 22 to 27
Irrigation on all plots: all plots at field capacity
Start of the experiments

13/1/1987 Flowering

10/3/1987 End of the experiments
Final irrigation

4/5/1987 Harvest plots 1 to 15

5/5/1987 Harvest plots 16 to 27

APPENDIX 2.2.9 AGRONOMIC PRACTISES FOR THE 1987 WINTER SEASON AT SITES D6, D12 AND D16.

22/6/1987	All soils at field capacity Fertilizer application on all plots 2ton/ha gypsum 150kg/ha superphosphate 300kg/ha ammoniumsulphate Sowing durum wheat cultivar: Moni 100kg seed per hectare rows 300mm apart
6/7/1987	Emergence Light irrigation
29/7/1987	Irrigation on all plots
5/8/1987	Fertilizer application on all plots 150kg/ha ammoniumsulphatenitrate Irrigation on all plots Start drying cycle on plots a
12/8/1987	Pest control treatment 500ml Metasystox and 650ml Parathion in 250 liter water
14/8/1987	Irrigation at all sites: plots b, c, d and e
24/8/1987	Irrigation at all sites: plots b, c, d and e Start drying cycle on plots b
28/8/1987	Weed control treatment 2liter/ha Bromoxynil + 1liter/ha MCPA in 500 liter water
10/9/1987	Irrigation at all sites: plots c, d and e Start drying cycle on plots c
1/10/1987	Irrigation at all sites: plots a, d and e Start drying cycle on plots d
12/10/1987	Irrigation at all sites: plots a, b and e
16/10/1987	Irrigation at all sites: plots c
18/10/1987	Flowering
23/10/1987	Irrigation at all sites: plots a, b, c and e
3/11/1987	Irrigation at sites D6 and D12: all plots
4/11/1987	Irrigation at site D16: all plots
4/12/1987	Harvest

APPENDIX 2.2.10 AGRONOMIC PRACTICES FOR THE 1987 WINTER SEASON AT SITE ISO (A-BLOK).

18/6/1987	Soils at field capacity Fertilizer application on all plots 3ton/ha gypsum 150kg/ha superphosphate 300kg/ha ammoniumsulphate Sowing wheat on all plots cultivar: Gamtoos 100kg seed per hectare rows 300mm apart
2/7/1987	Emergence Light irrigation on all plots
3/8/1987	Fertilizer application on all plots 150kg/ha ammoniumsulphate Irrigation on all plots Start experiments
12/8/1987	Pest control treatment 500ml Metasystox and 650ml Parathion in 250 liter water
21/8/1987	Weed control treatment 2 liter/ha Bromoxynil + 1 liter/ha MCPA in 500 liter water
12/10/1987	Flowering
19/11/1987	End of the experiments
2/12/1987	Harvest

APPENDIX 2.2.11 AGRONOMIC PRACTICES FOR THE 1987-1988 SUMMER SEASON AT SITE ISO (B-BLOK).

21/9/1987 Prepare plots
Irrigation on all plots

6/10/1987 to
8/10/1987 Prepare plots
Fertilizer application on all plots
3ton/ha gypsum

9/10/1987 Irrigation on all plots: all plots at field capacity

15/10/1987 Fertilizer application on all plots
150kg/ha superphosphate
200kg/ha ammoniumsulphate

20/10/1987 Planting maize on all plots
cultivar: Pioneer PNR 542
40000 plants per hectare
rows 1m apart, plants 250mm apart

28/10/1987 Emergence
Light irrigation on all plots

9/11/1987 Irrigation on all plots

11/11/1987 Thinning out

12/11/1987 Fertilizer application on all plots
250kg/ha ammoniumsulphate
No irrigation, rain

20/11/1987 Irrigation on all plots
Soils at field capacity
Start experiments

4/12/1987 Weed control treatment
2 liter/ha Bactril diluted in 500 liter water

17/2/1988 Irrigation on all plots
End of the experiments

1/6/1988 Harvest

APPENDIX 2.3 STATISTICAL ANALYSIS OF THE RELATIONSHIP BETWEEN LEAF LENGTH AND LEAF AREA PARAMETER (LAP) FOR MAIZE PLANTS (PIONEER PNR 542).

The data used for this analysis were collected during the 1985-1986 summer season at sites D6, D12 and D16. The regression analysis is given in Table 2.3.1. The data are plotted out in Figure 2.3.1.

Table 2.3.1 Regression analysis

Dependent variable: leaf area parameter
Independent variable: total length of the leaves of a plant
Number of data: 115

Variable	coeff	std err	T-stat
constant	-1897	115	-16,46
total length	1,125	0,02	68,45
R-sq	0,976	corr R-sq	.976

Because the variable leaf area parameter includes the variable total leaf length, there are some objections to this approach from a purist statistical point. It was therefore decided to study the relationships between leaf length and leaf width for the data collected in the 1985-1986 summer season.

For plots D6a and D6a and D12a combined total lengths of all leaves of a specific plant measured at a specific time were correlated with total width of all leaves measured at the same time. The results are illustrated in Figures 2.3.2 and 2.3.3 and Table 2.3.2.

For plot D16a an analysis was made for single leaf values (instead of total leaves per single plant). The analysis was done for all leaves and the results are illustrated in Figure 2.3.4 and Table 2.3.2.

Table 2.3.2 Leaf width/leaf length relationships for maize (Pioneer PNR 542)

Plot	width/length factor	regression coefficient (R-sq)
D6a	0,125	0,96
D12a	0,127	0,95
D6a + D12a	0,125	0,96
D16a	0,123	0,86

The correlations between leaf length and leaf width were very good, even where single leaf values were used. This largely contributes to the excellent correlations between leaf length and leaf area parameter.

The leaf width/leaf length factor was very consistent for all plots when all leaves were included (both for total leaf and single leaf analyses). The factors ranged from 0,123 to 0,127.

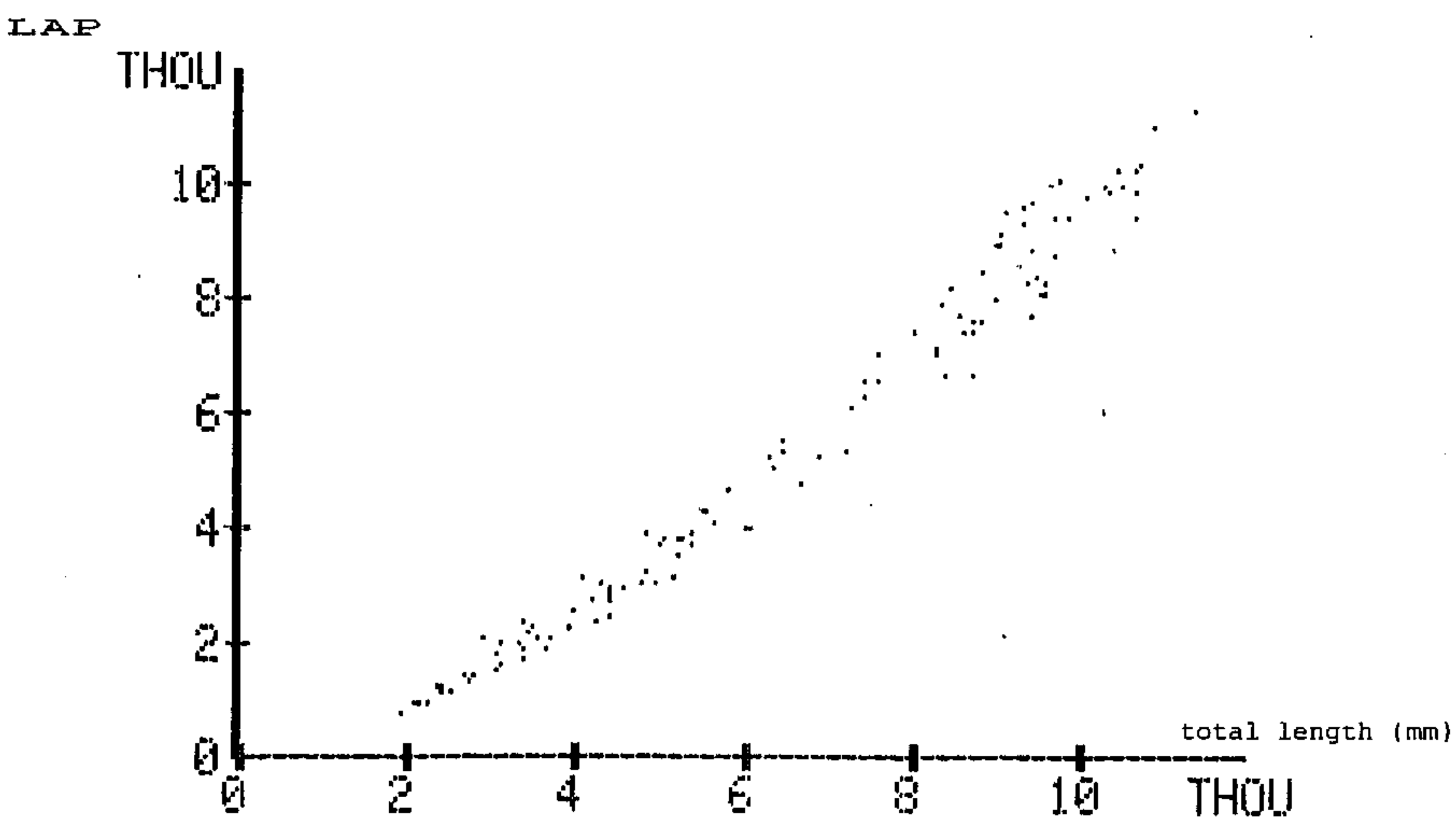


FIG. 2.3.1 Relationship between total length of the leaves of a maize plant and the leaf area parameter (LAP).

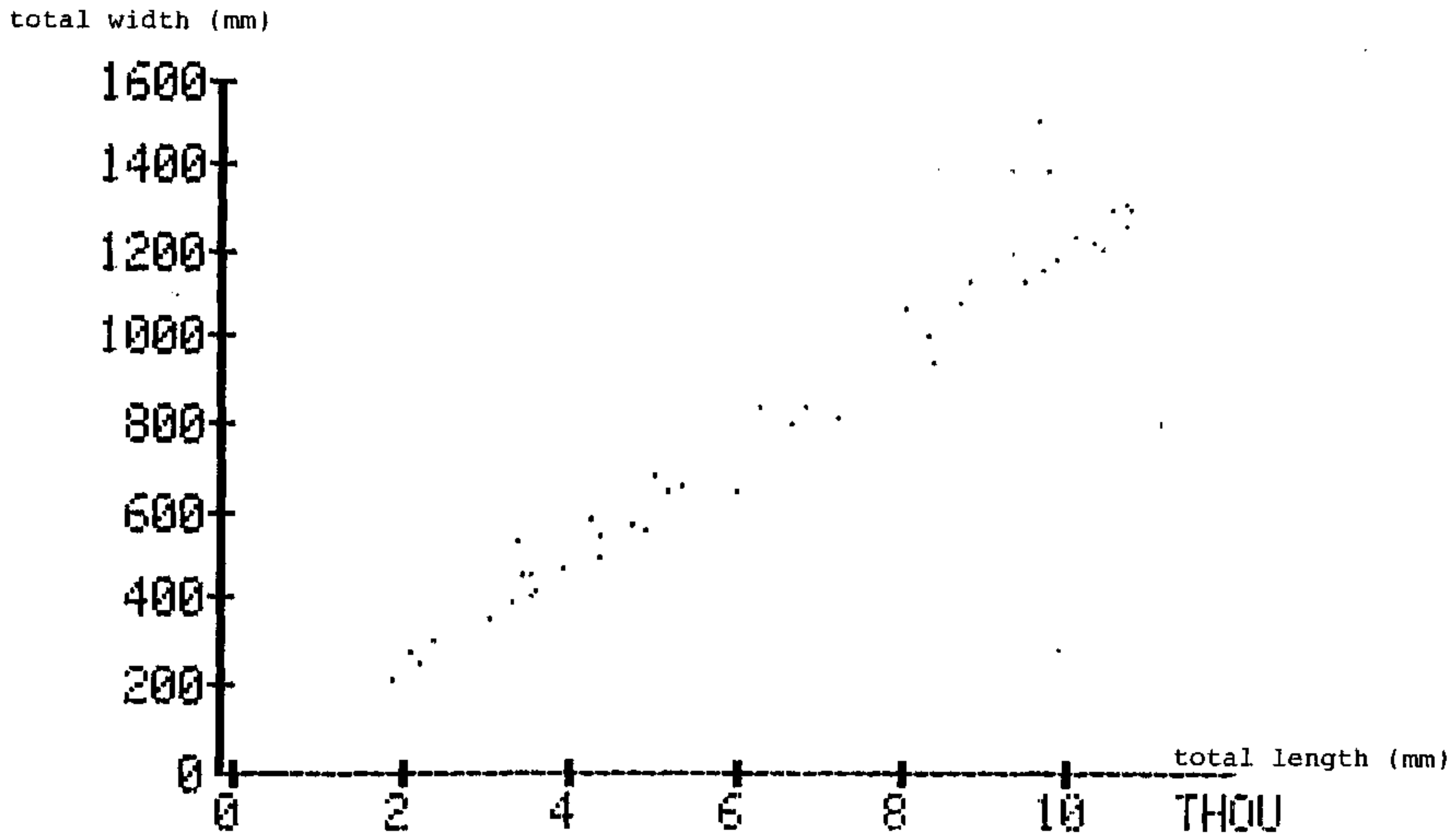


FIG. 2.3.2 Relationship between total leaf length and total leaf width of maize plants on plot D6a.

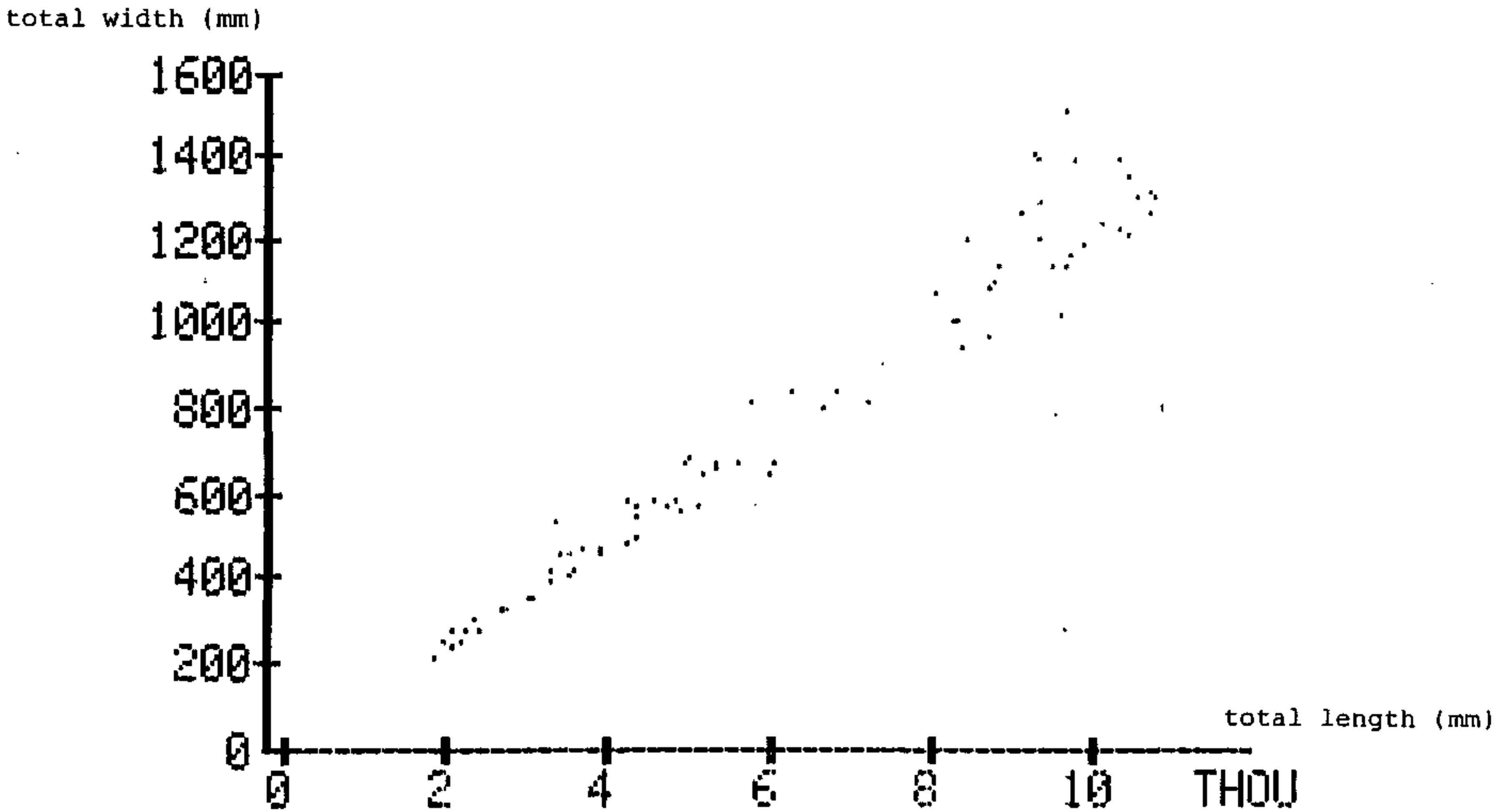


FIG. 2.3.3 Relationship between total leaf length and total leaf width of maize plants on plots D6a and D12a.

a 2.3

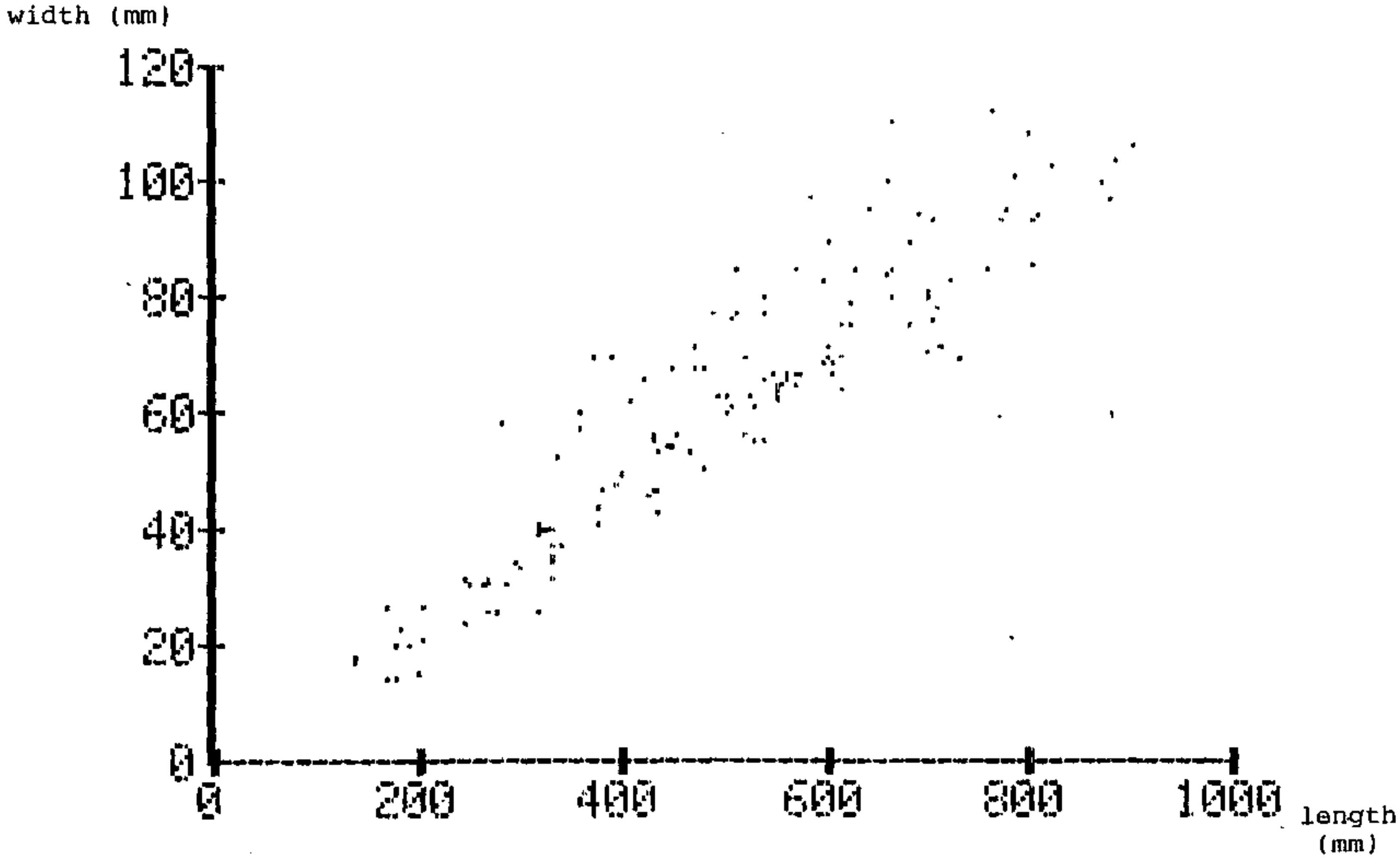
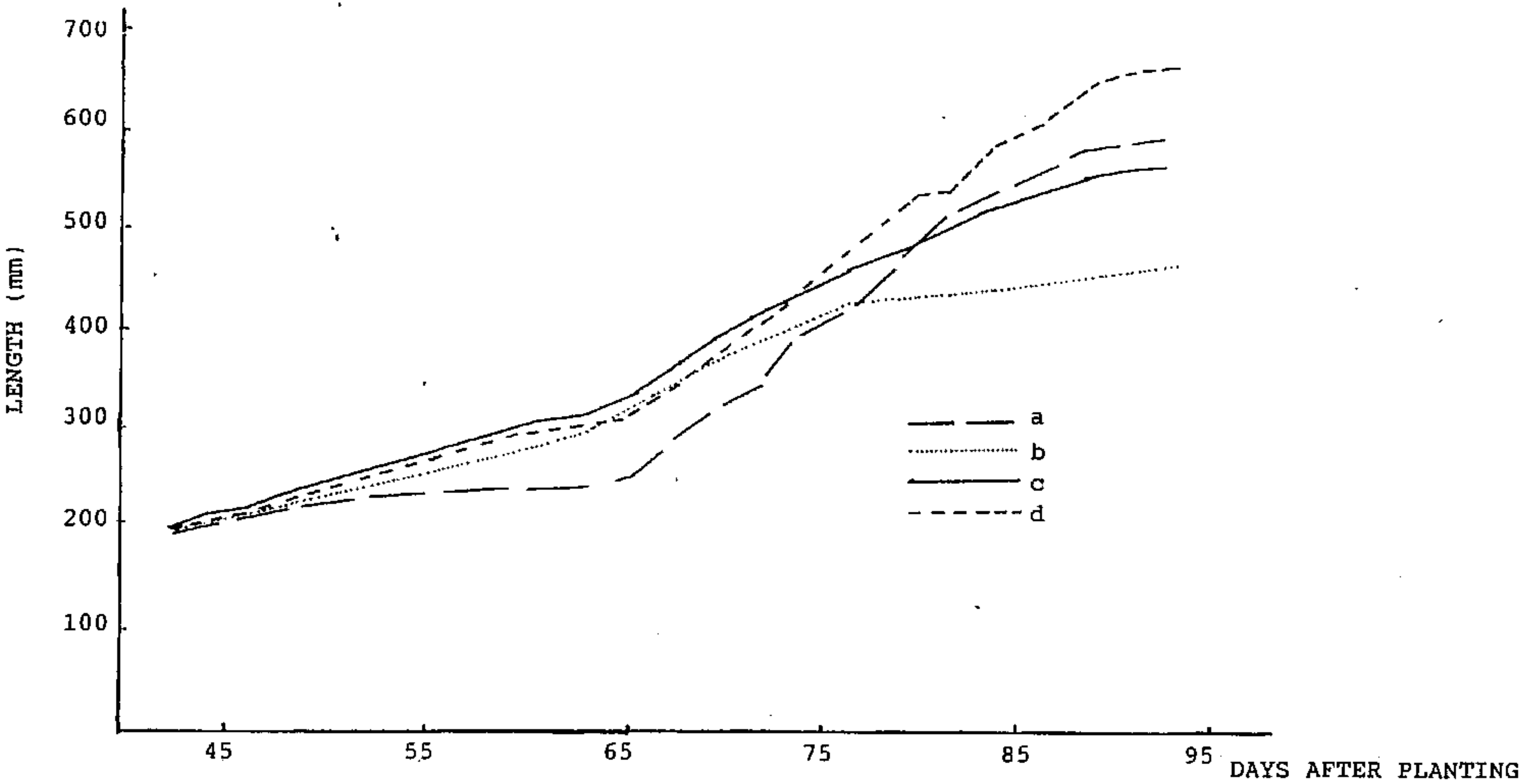
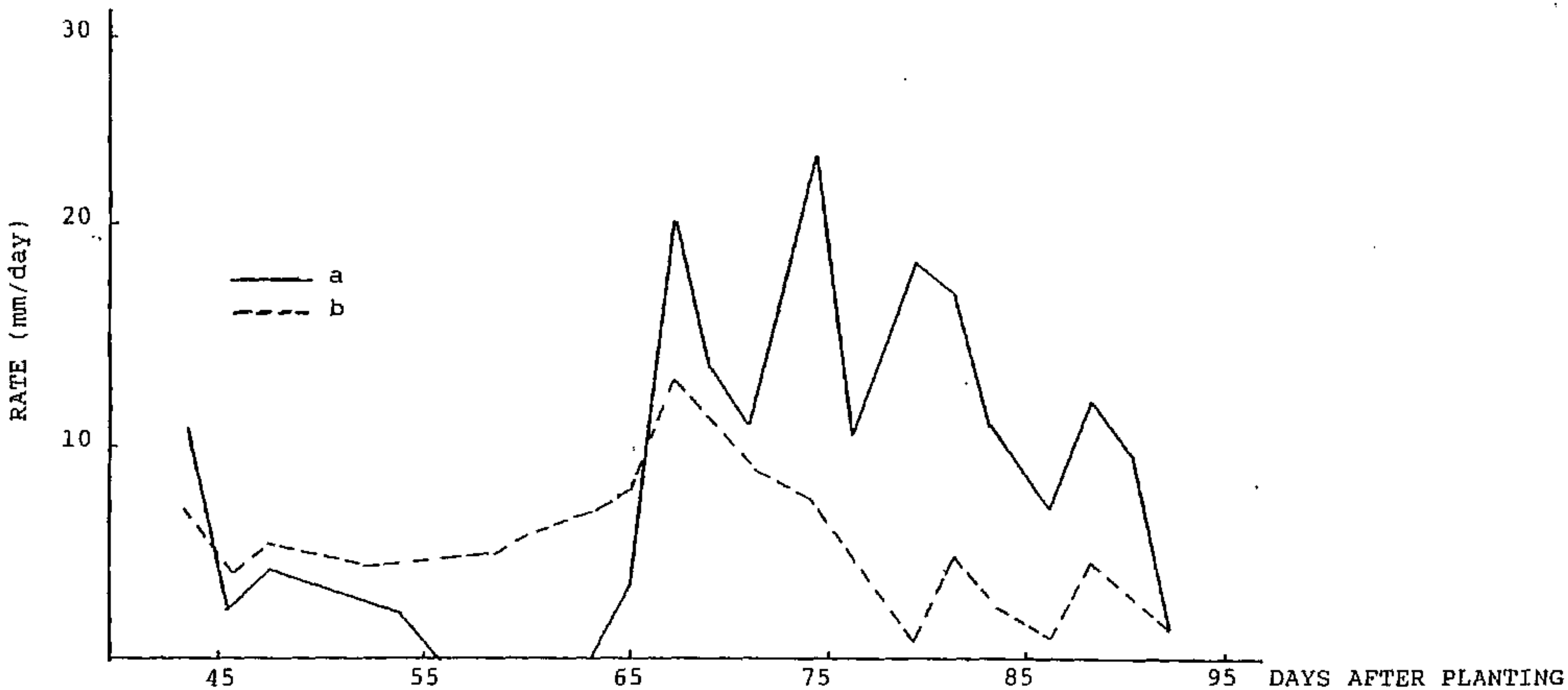


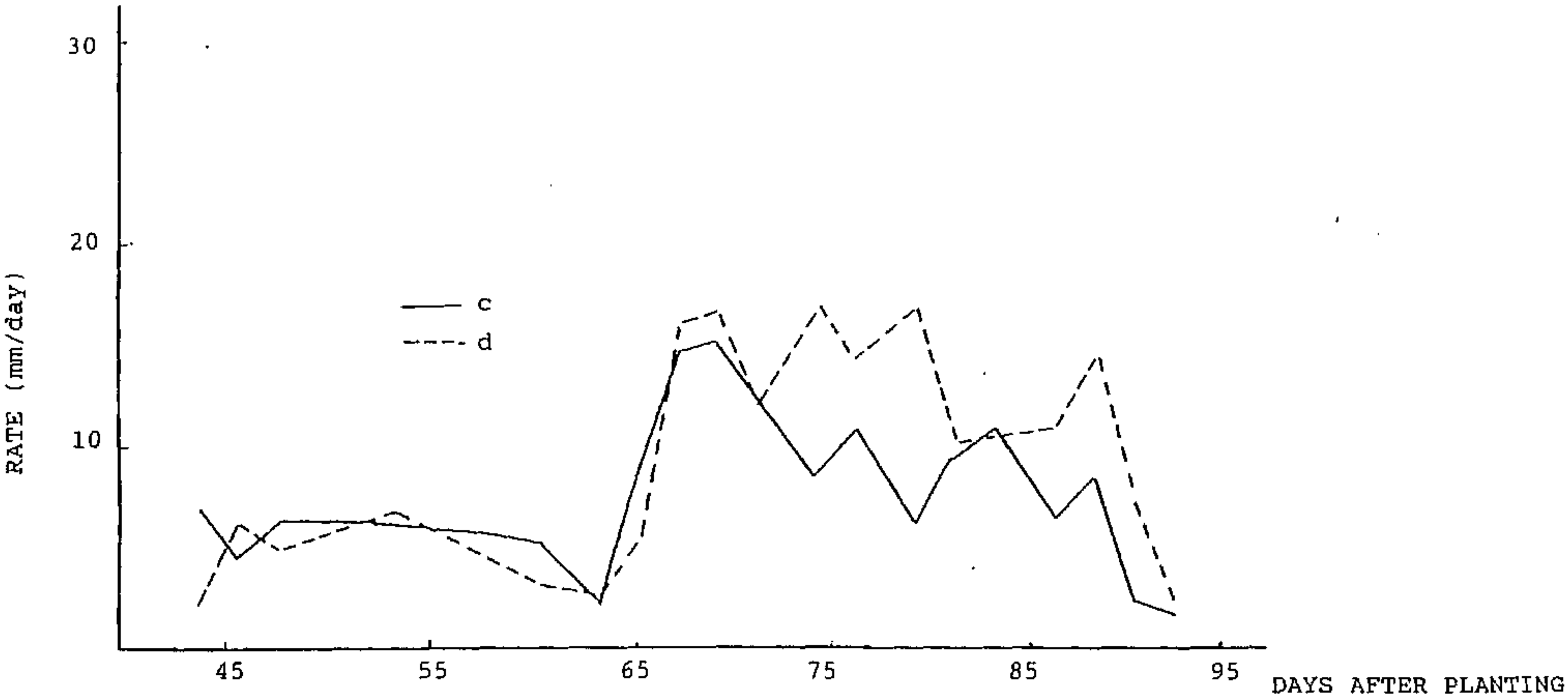
FIG. 2.3.4 Relationship between width and length of individual leaves of maize plants on plot D16a.



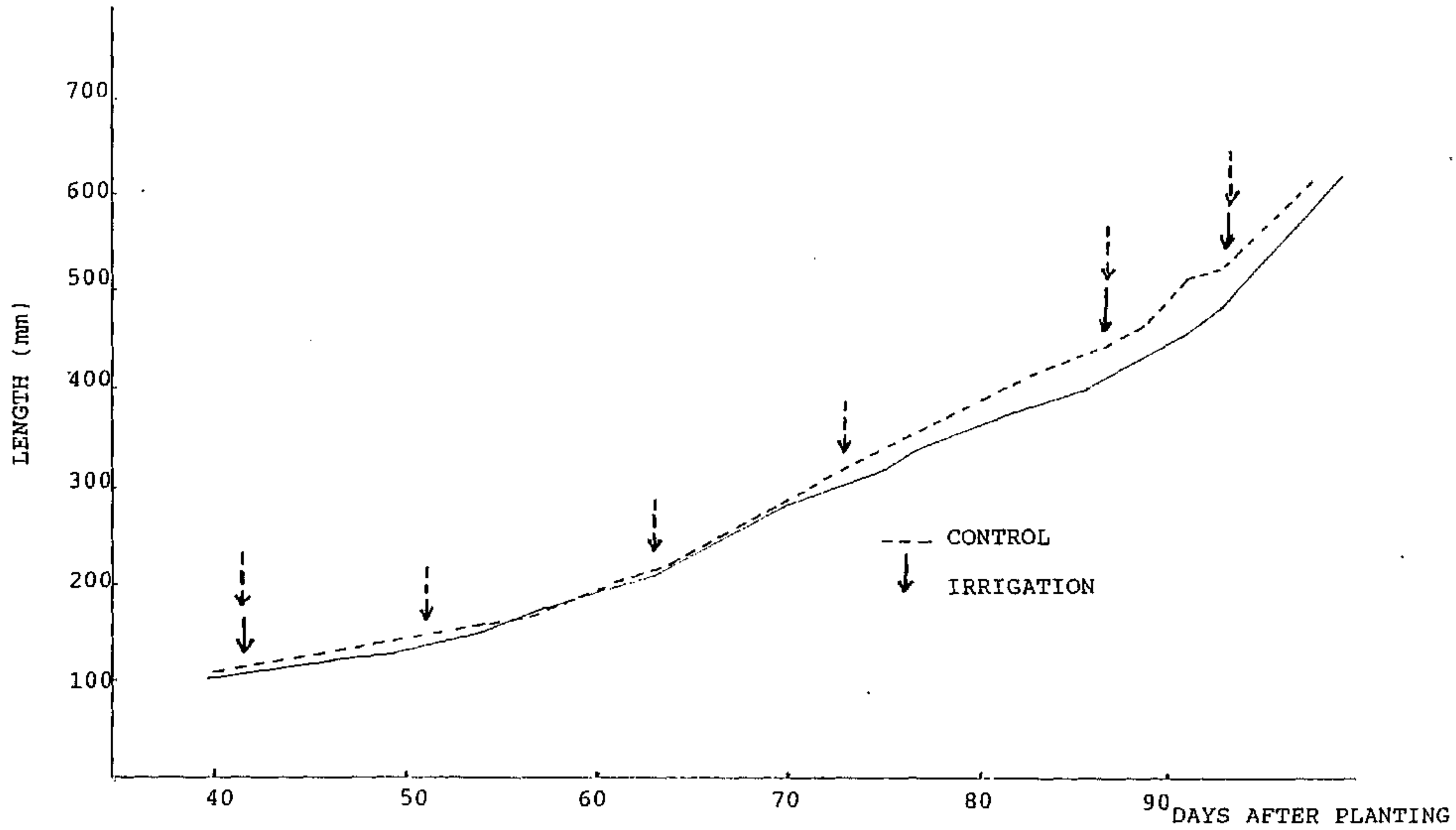
APPENDIX 3.1.1 CUMULATIVE STEM ELONGATION OF WHEAT AT SITE D12 (1985 SEASON)



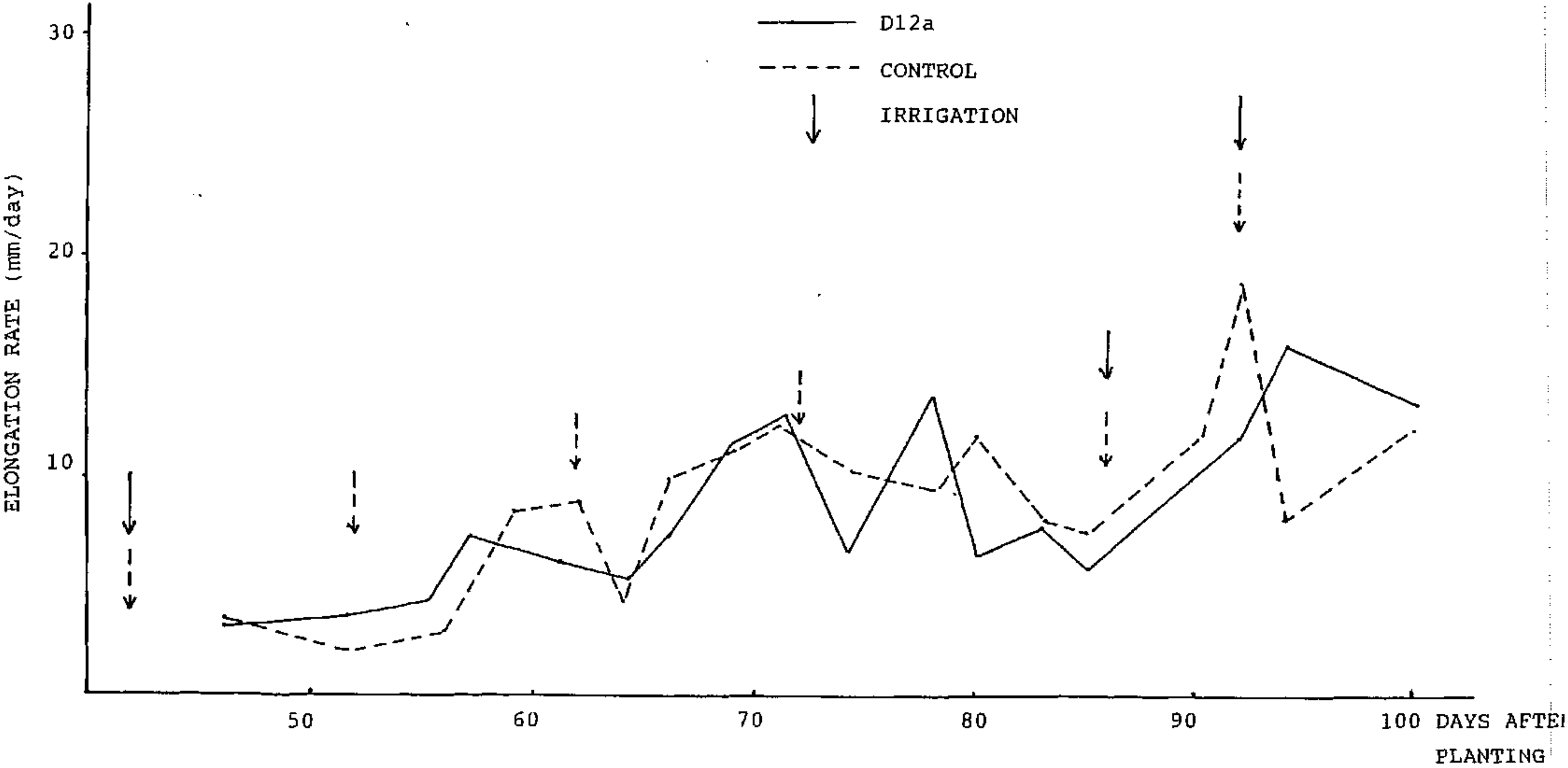
APPENDIX 3.1.2 STEM ELONGATION RATE OF WHEAT AT SITE D12 (1985 SEASON)



APPENDIX 3.1.3 STEM ELONGATION RATE OF WHEAT AT SITE D12 (1985 SEASON)

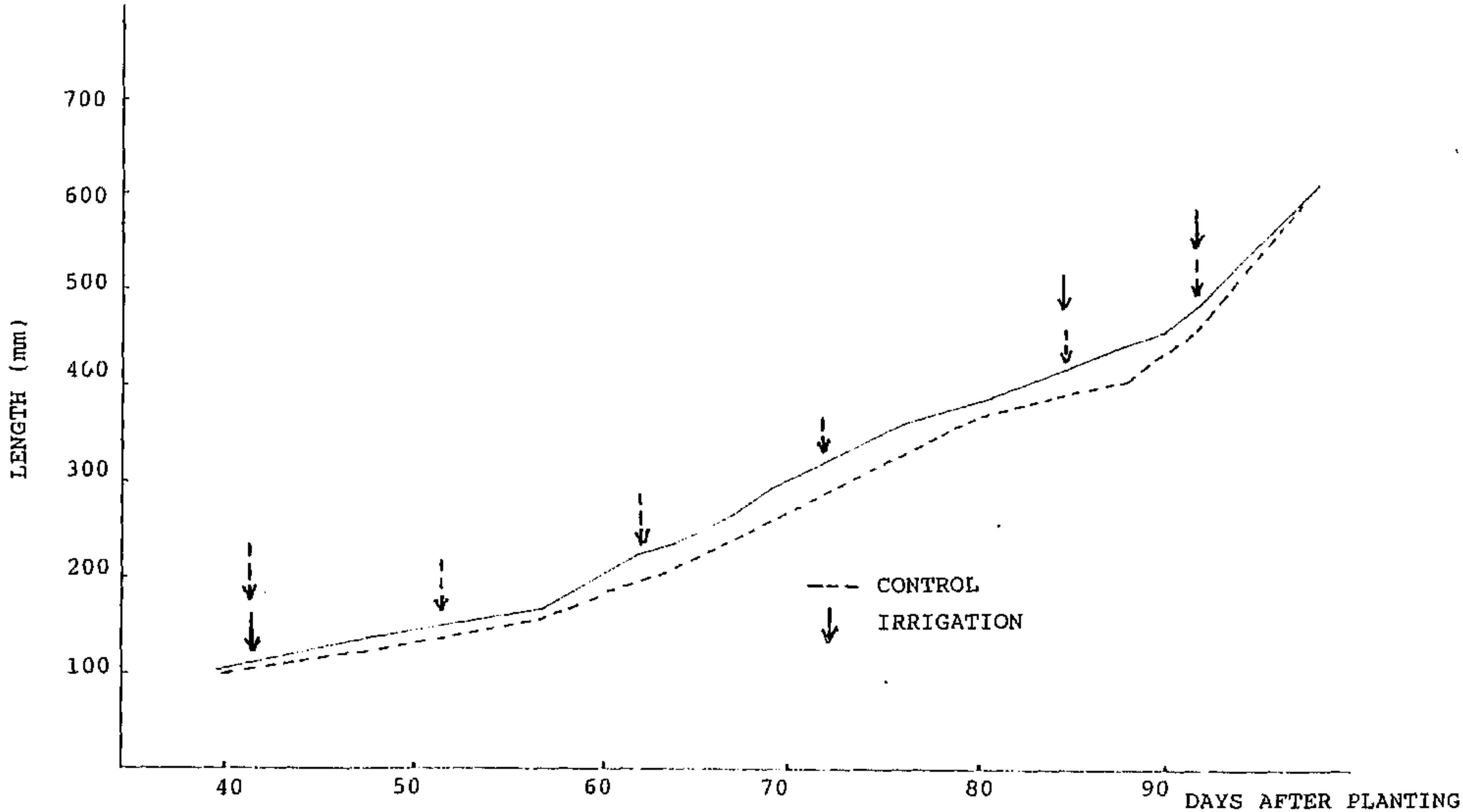


APPENDIX 3.1.4 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D12a (1986 SEASON)

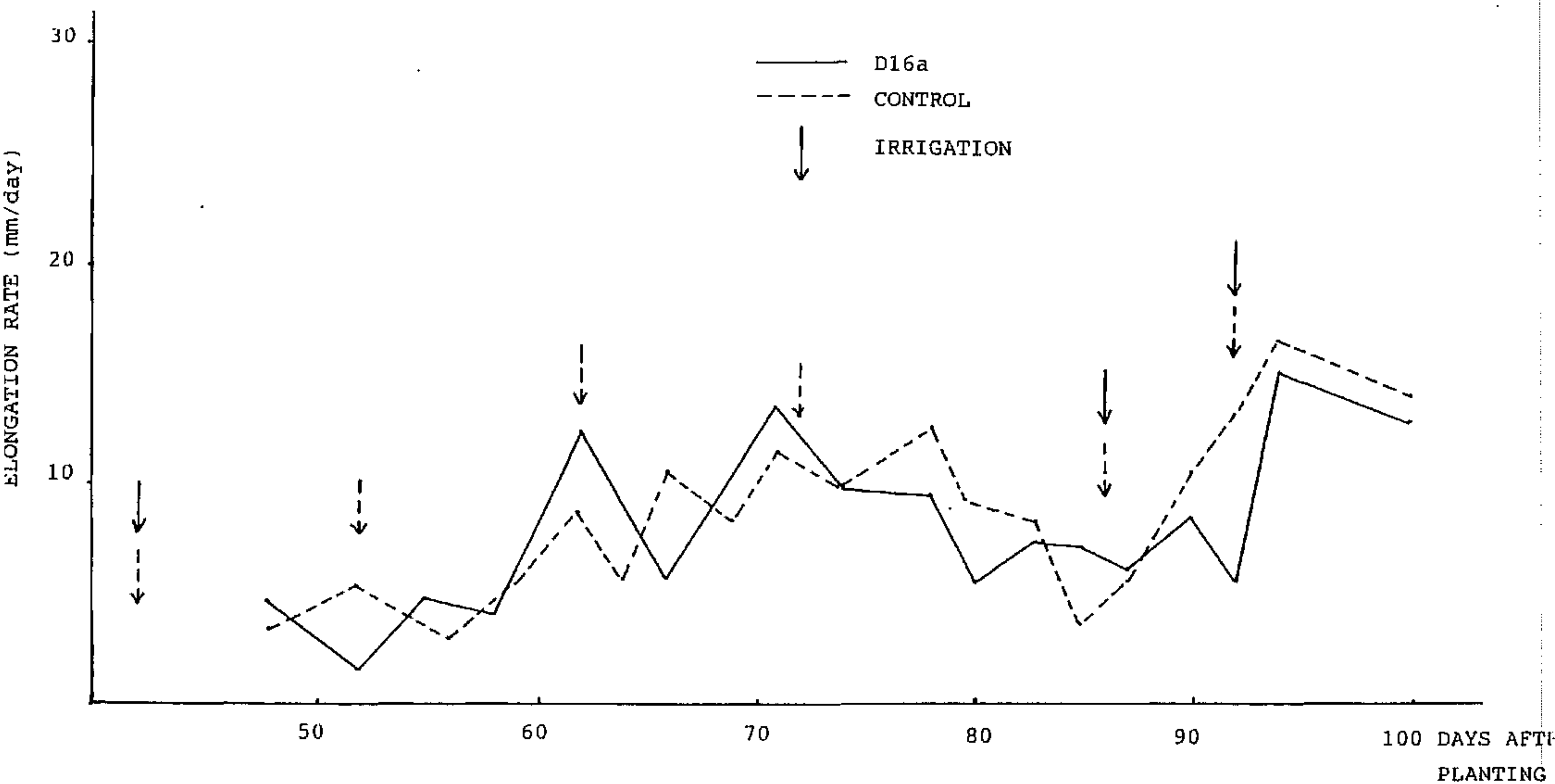


APPENDIX 3.1.5 STEM ELONGATION RATE OF WHEAT ON PLOT D12a (1986 SEASON)

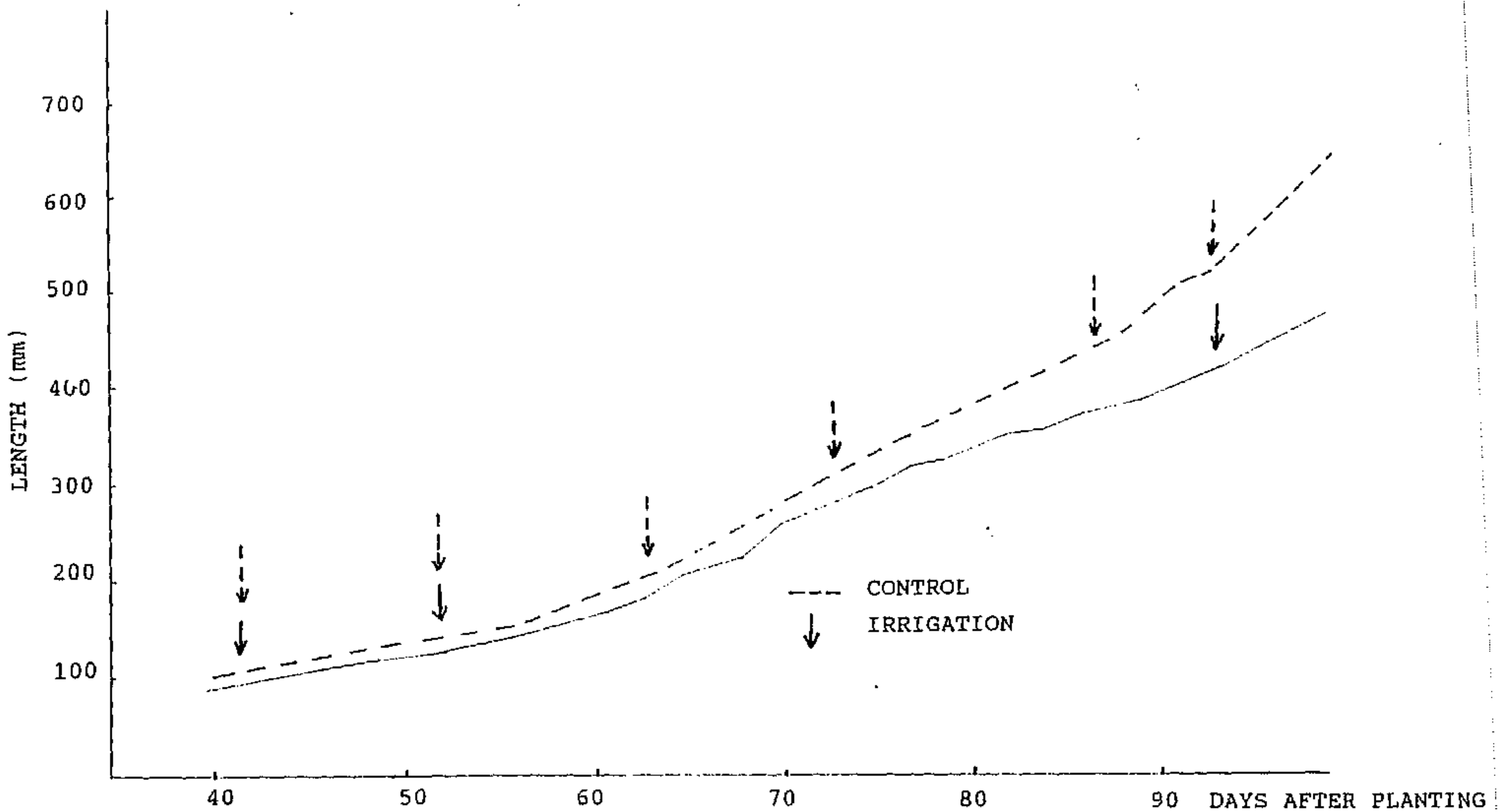
a 3.1



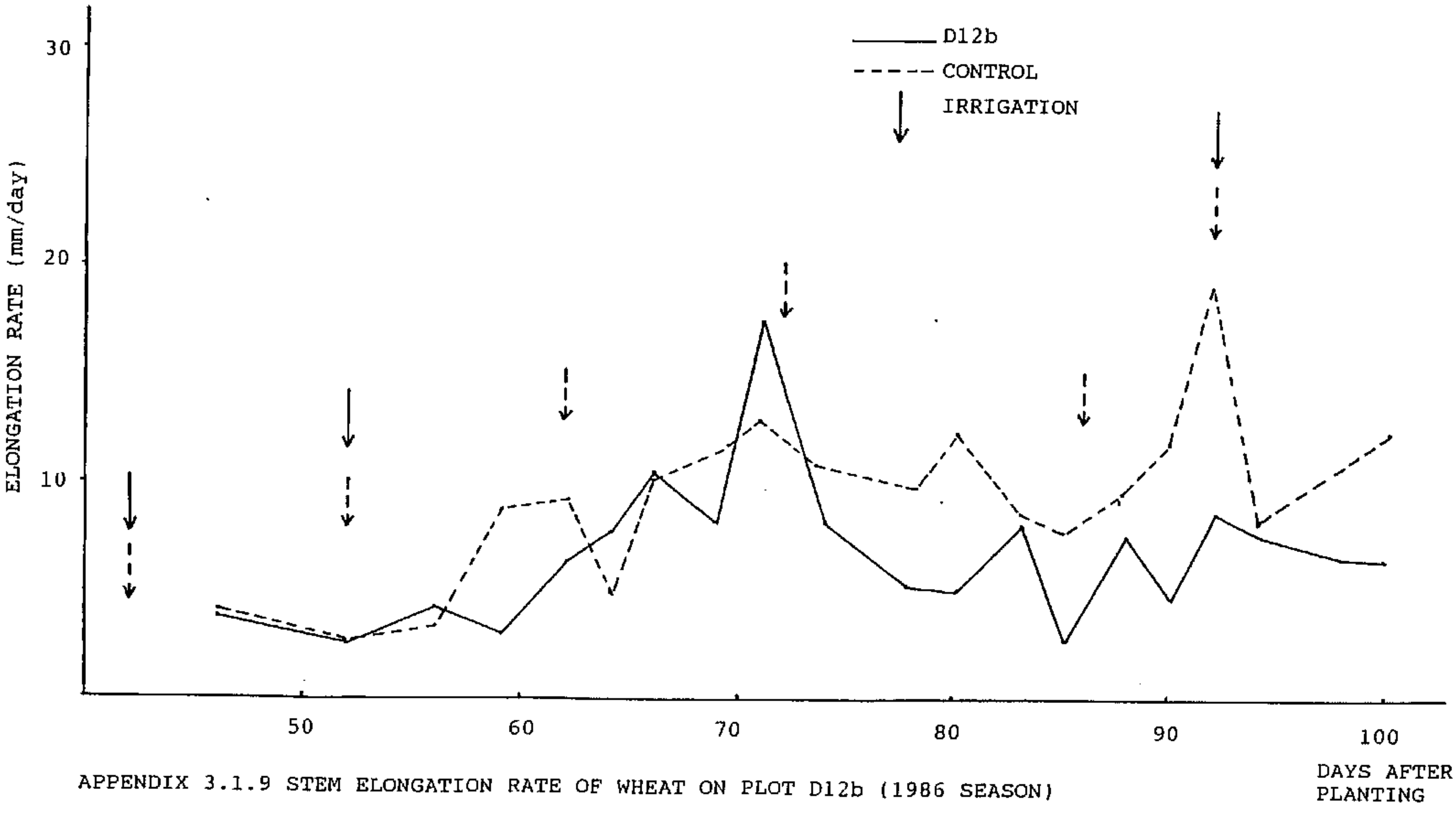
APPENDIX 3.1.6 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D16a (1986 SEASON)



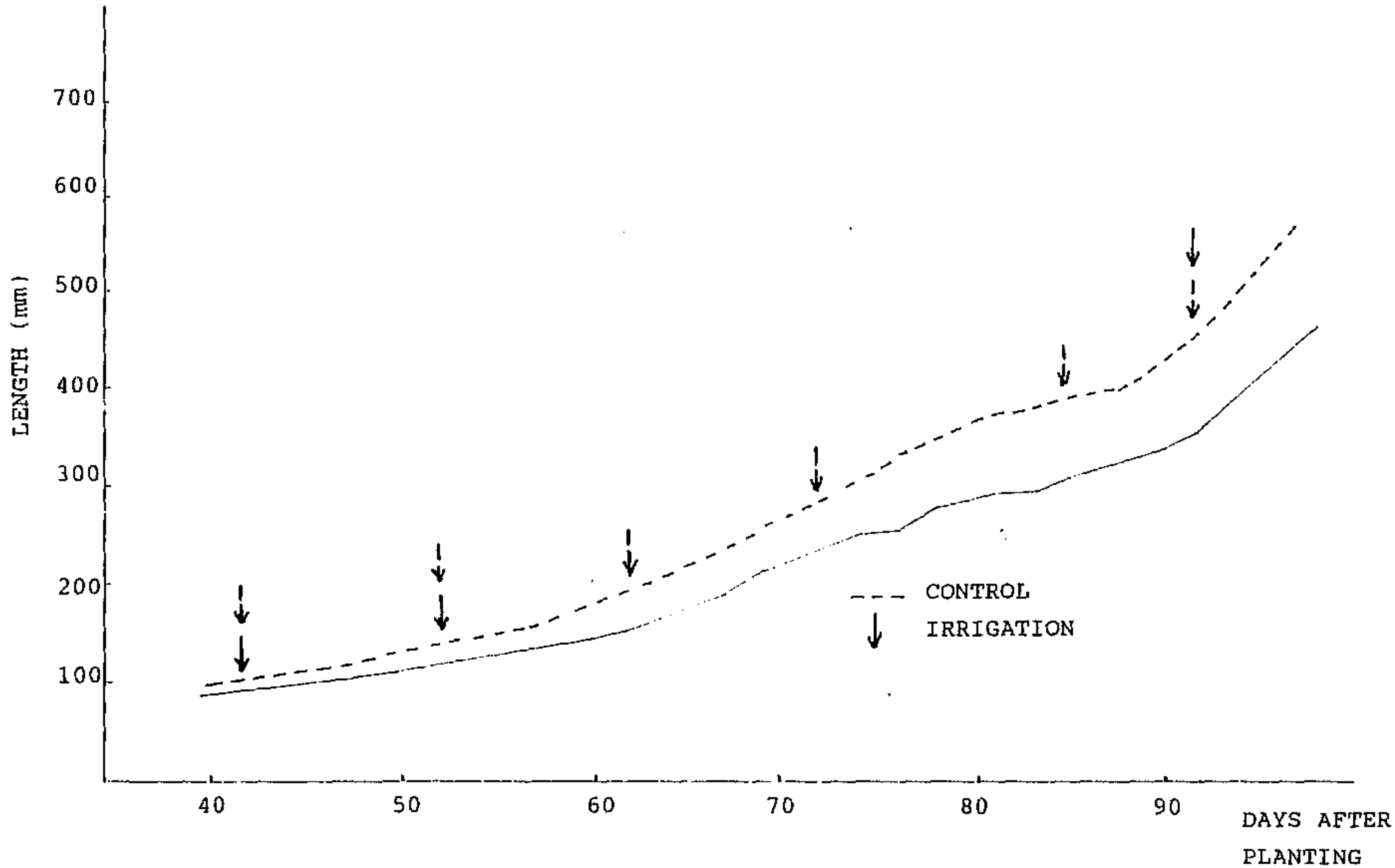
APPENDIX 3.1.7 STEM ELONGATION RATE OF WHEAT ON PLOT D16a (1986 SEASON)



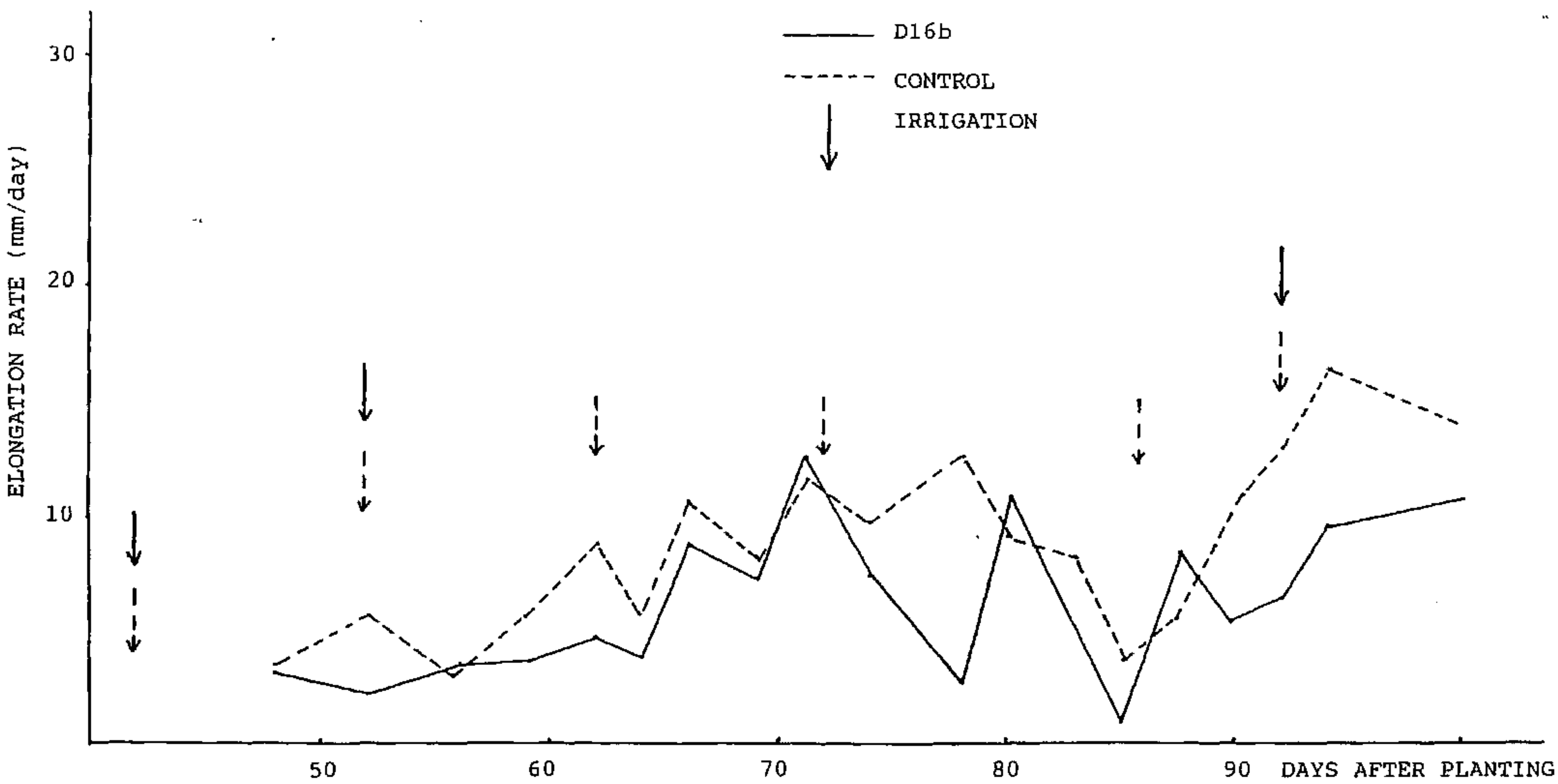
APPENDIX 3.1.8 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D12b (1986 SEASON)



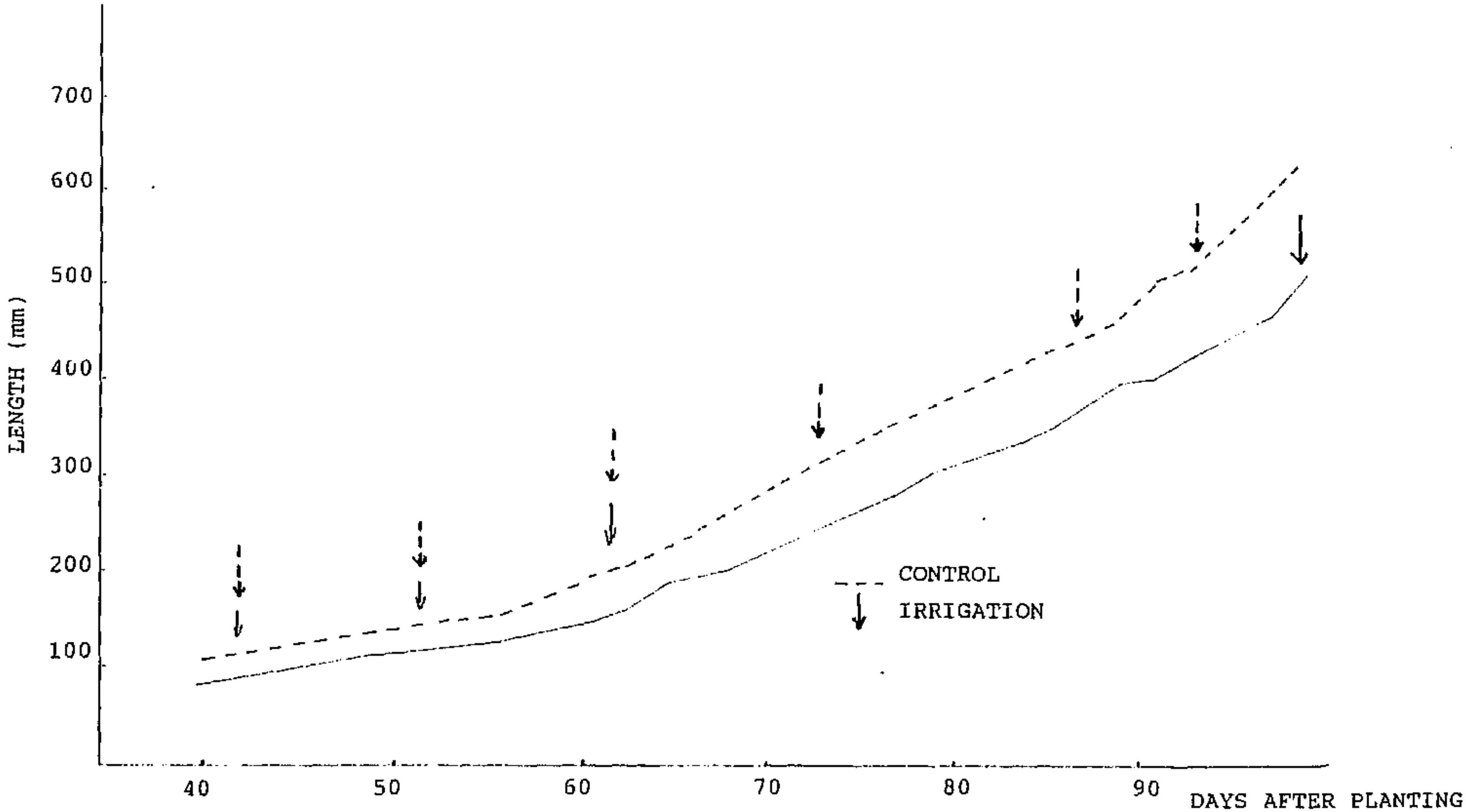
APPENDIX 3.1.9 STEM ELONGATION RATE OF WHEAT ON PLOT D12b (1986 SEASON)



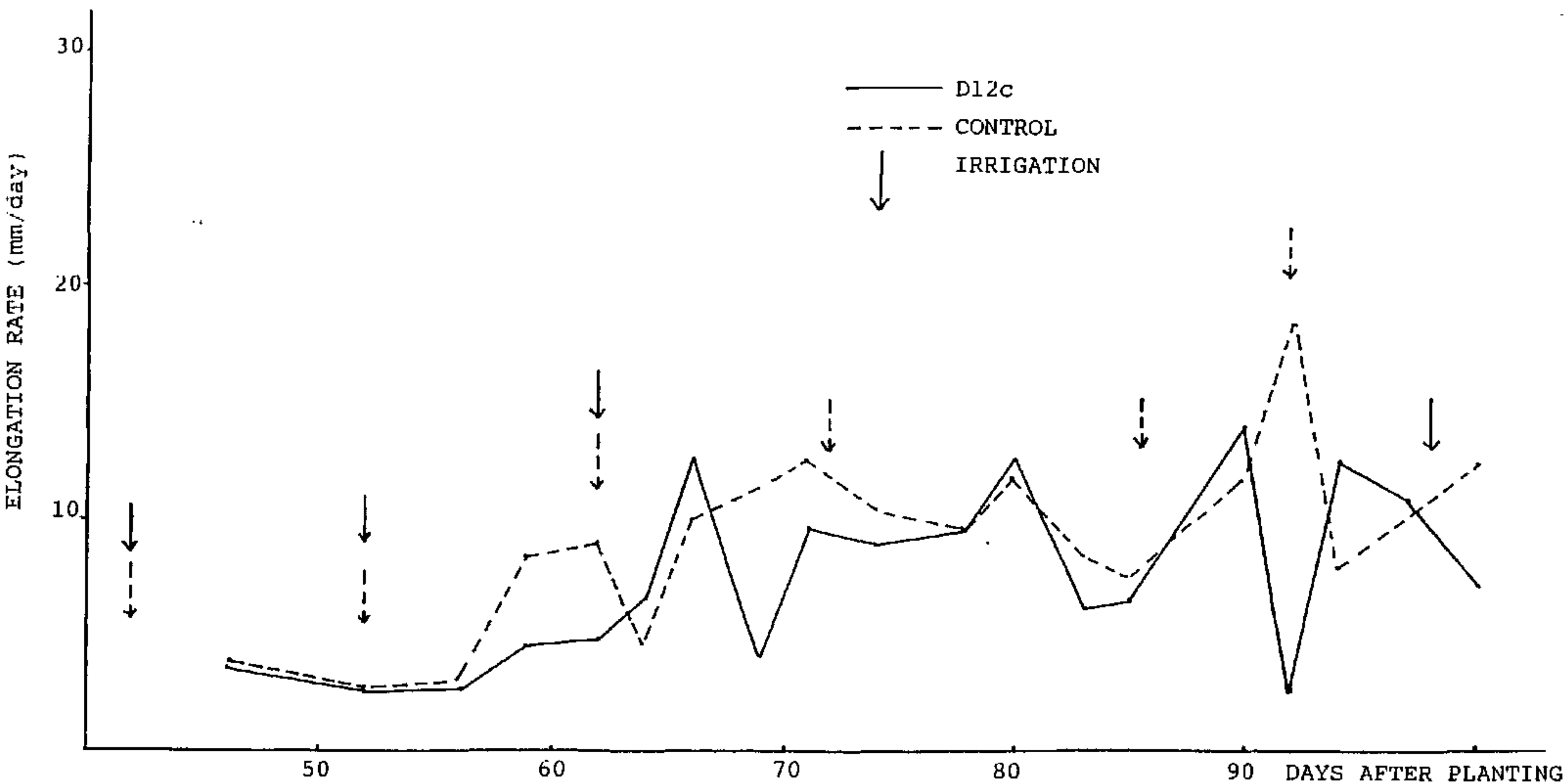
APPENDIX 3.1.10 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D16b (1986 SEASON)



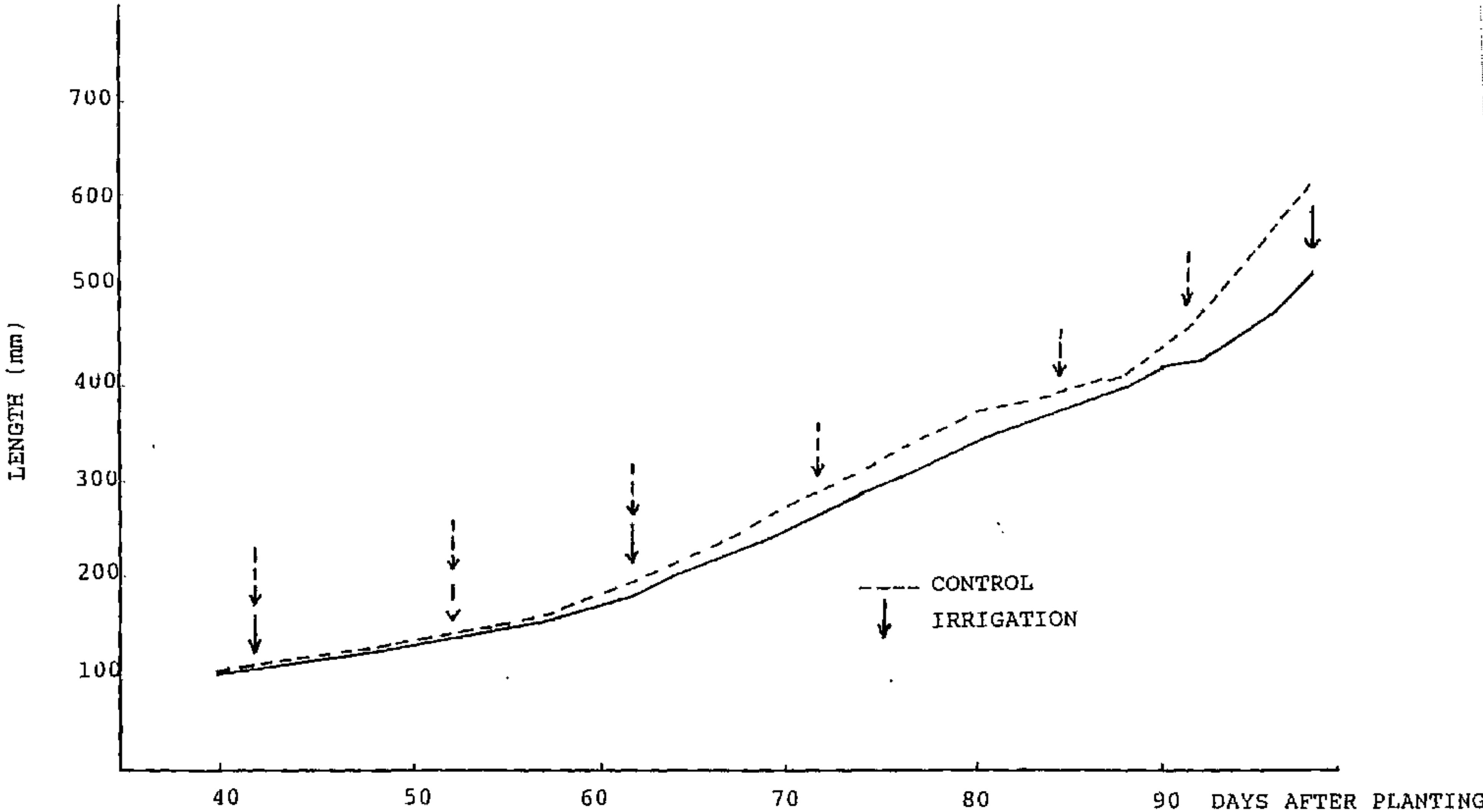
APPENDIX 3.1.11 STEM ELONGATION RATE OF WHEAT ON PLOT D16b (1986 SEASON)



APPENDIX 3.1.12 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D12c (1986 SEASON)

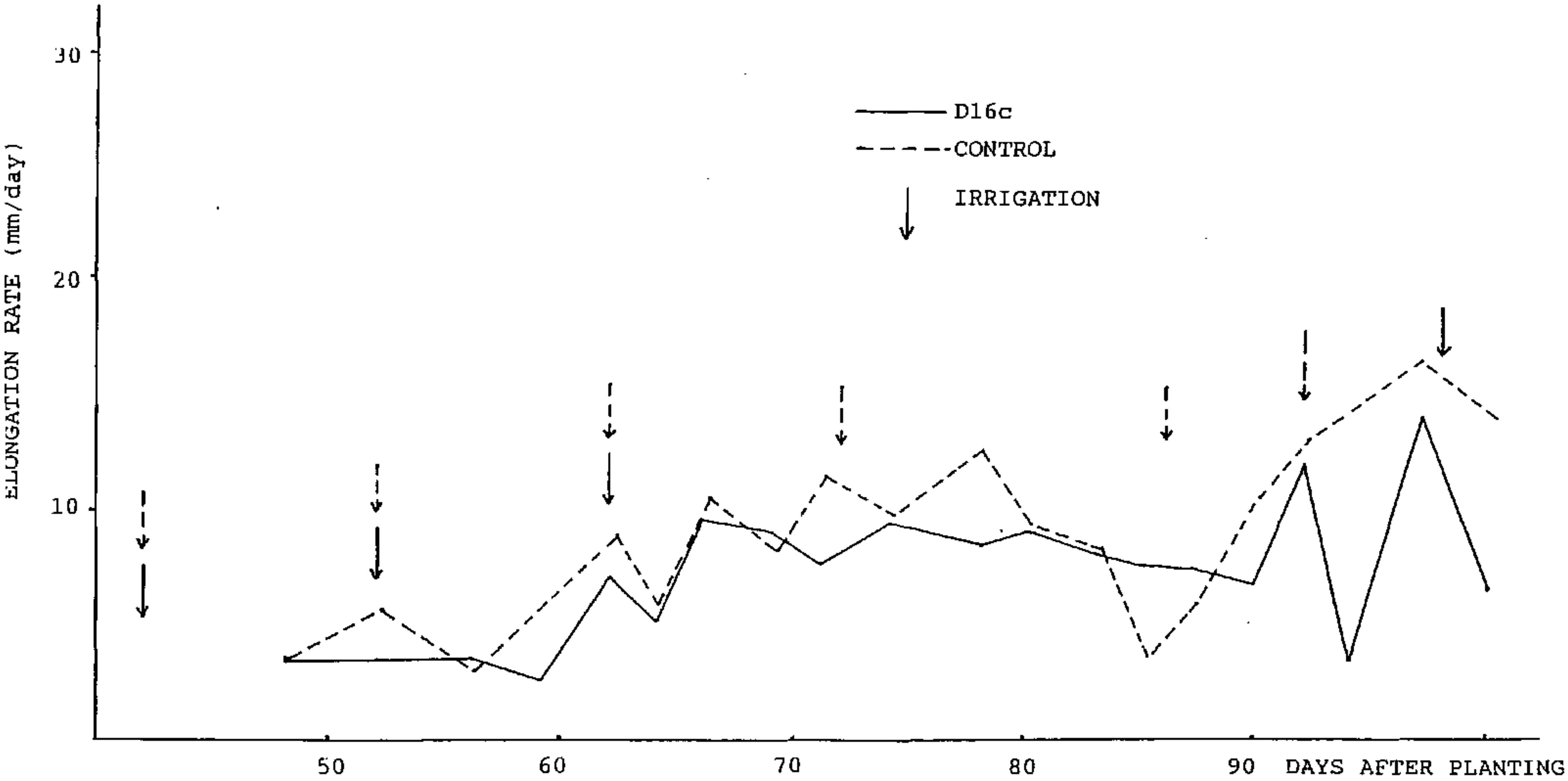


APPENDIX 3.1.13 STEM ELONGATION RATE OF WHEAT ON PLOT D12c (1986 SEASON)



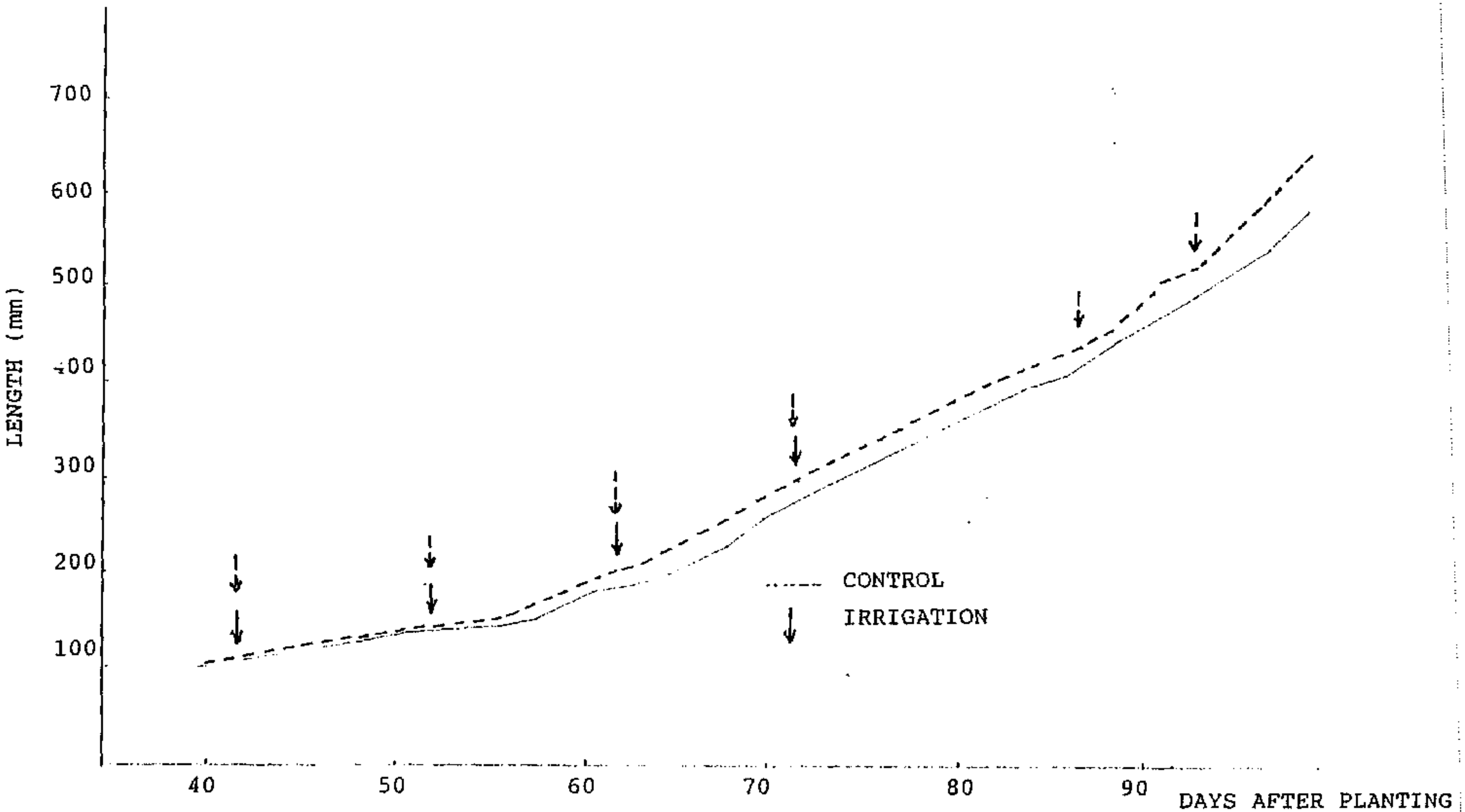
APPENDIX 3.1.14 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D16c (1986 SEASON)

a 3.1



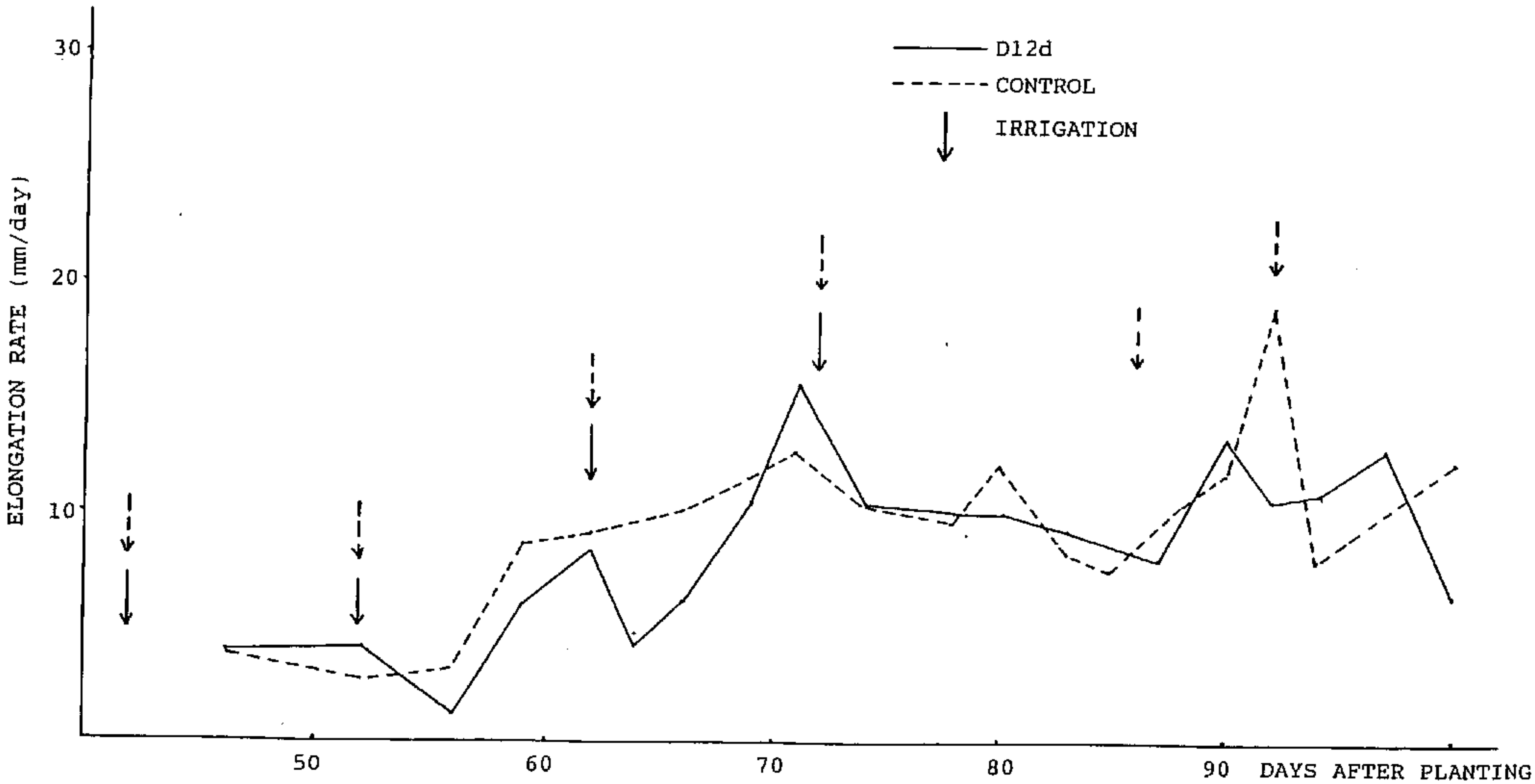
APPENDIX 3.!.!5 STEM ELONGATION RATE OF WHEAT ON PLOT D16c (1986 SEASON)

a 3.1

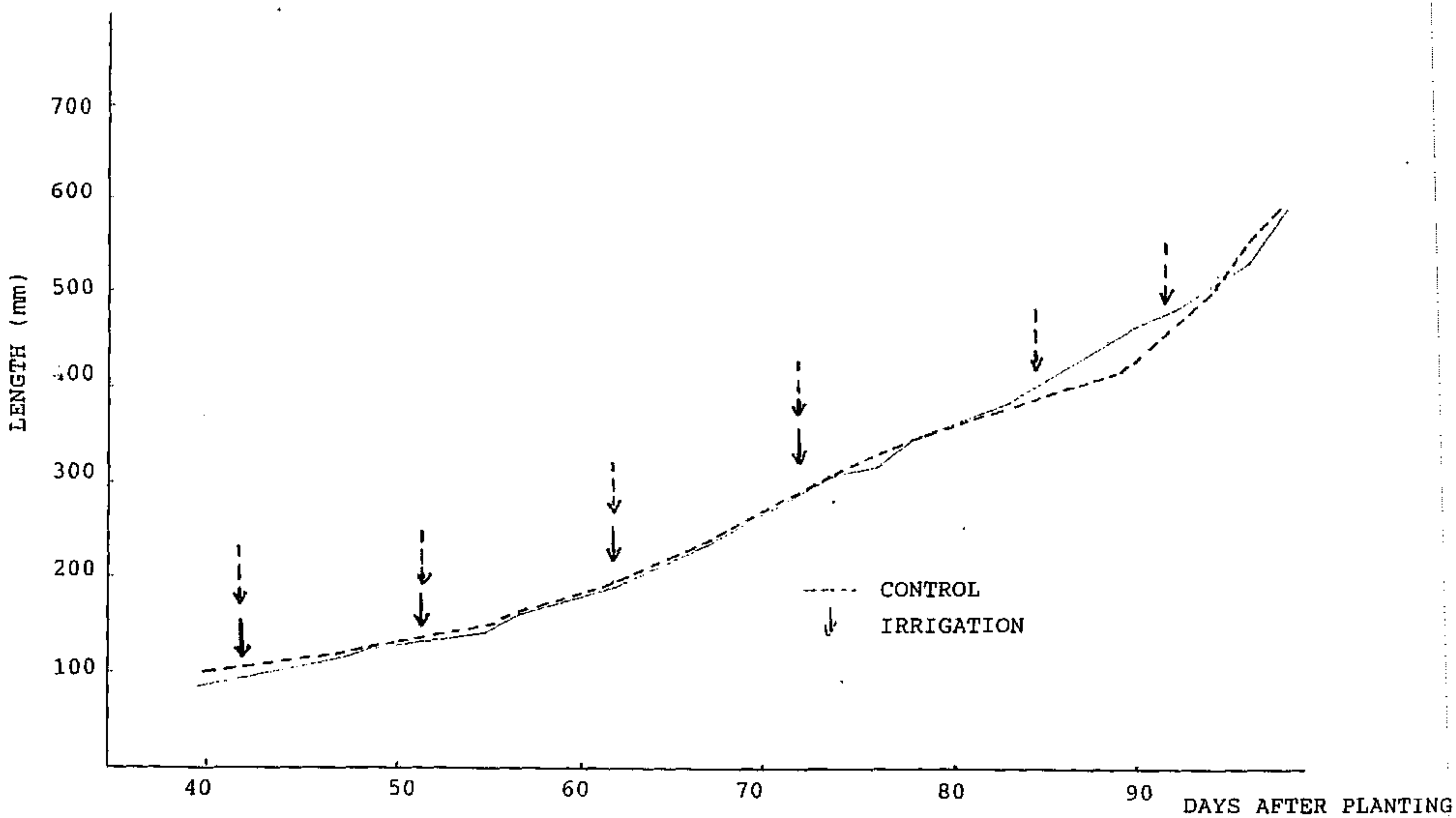


APPENDIX 3.1.16 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D12d (1986 SEASON)

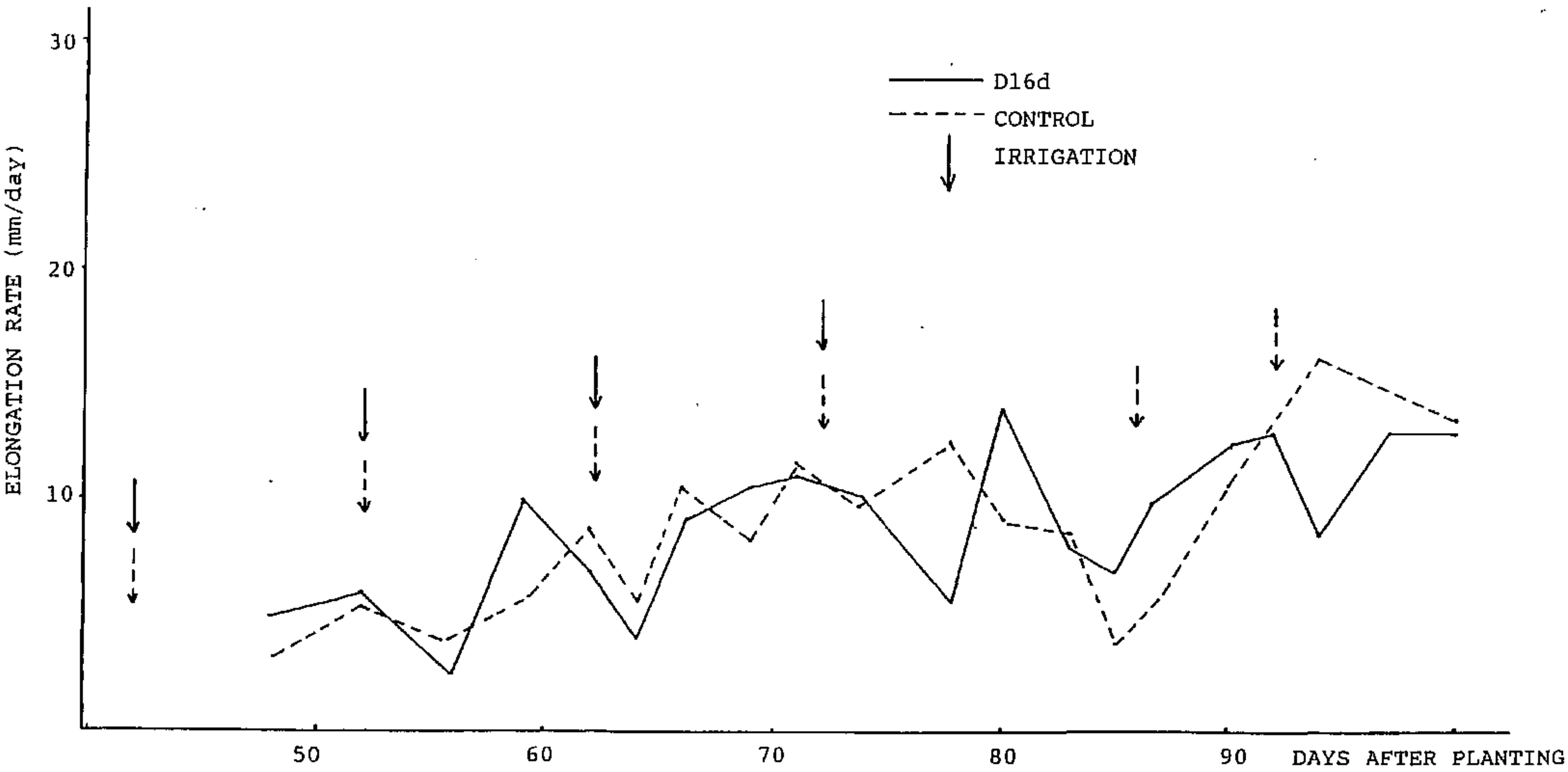
a 3.1



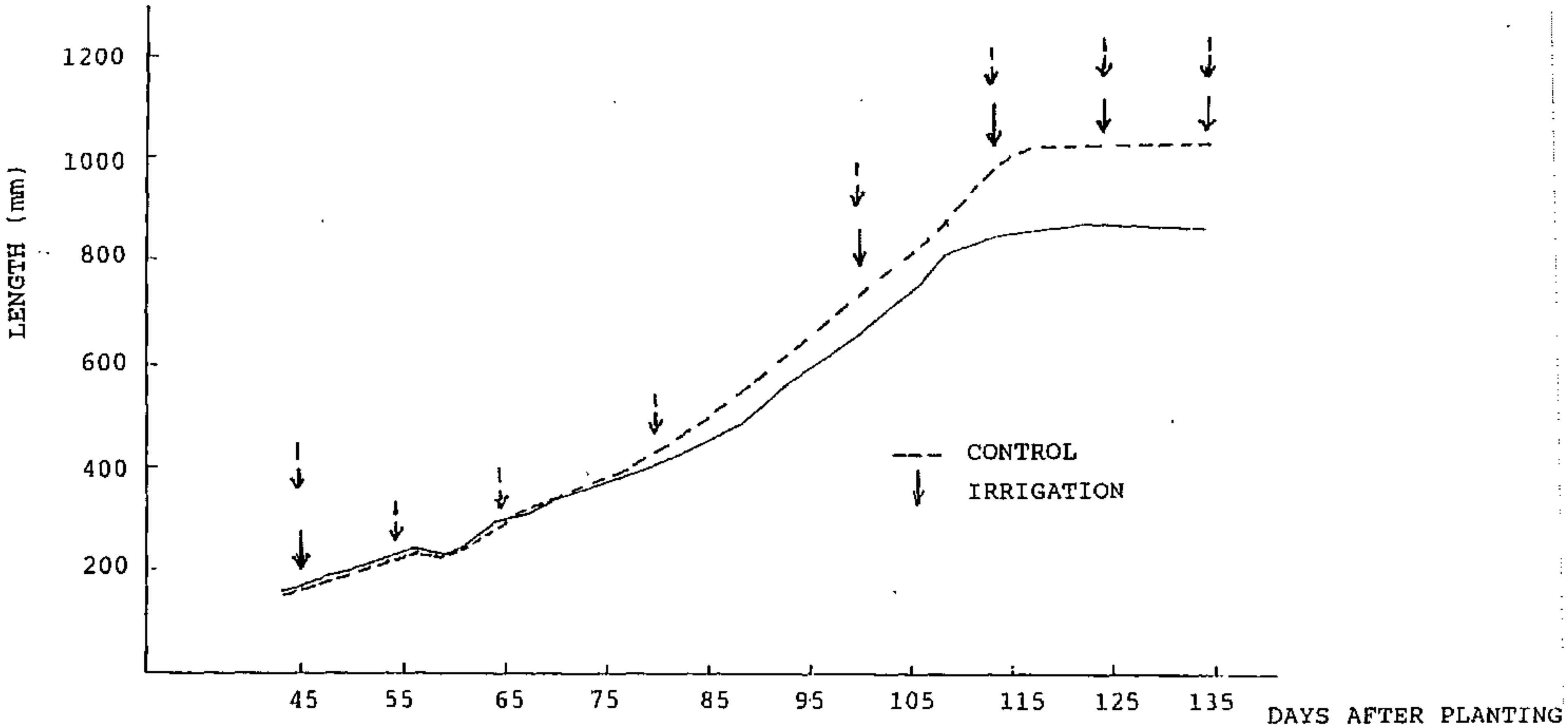
APPENDIX 3.1.17 STEM ELONGATION RATE OF WHEAT ON PLOT D12d (1986 SEASON)



APPENDIX 3.1.18 CUMULATIVE STEM ELONGATION OF WHEAT ON PLOT D16d (1986 SEASON)

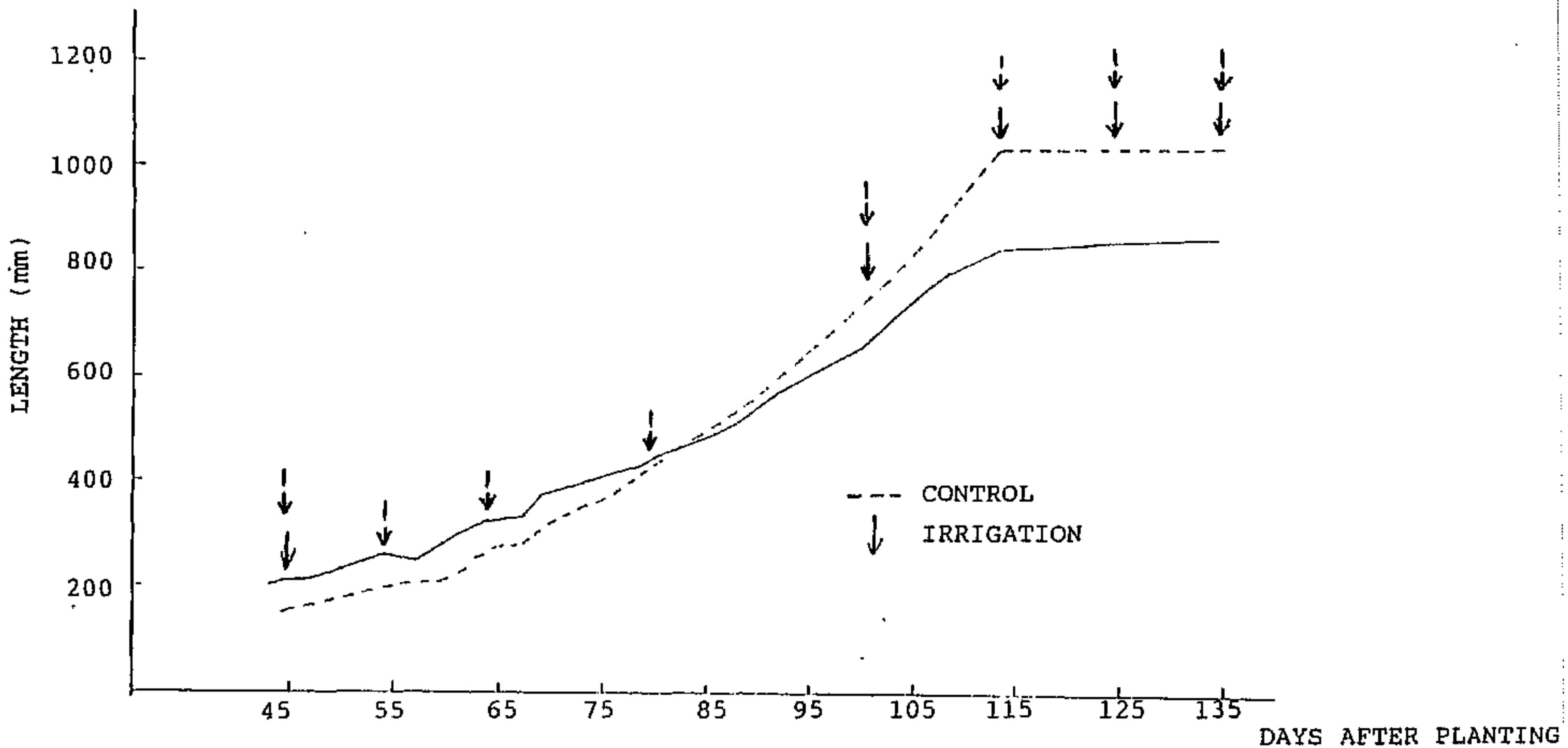


APPENDIX 3.1.19 STEM ELONGATION RATE OF WHEAT ON PLOT D16d (1986 SEASON)

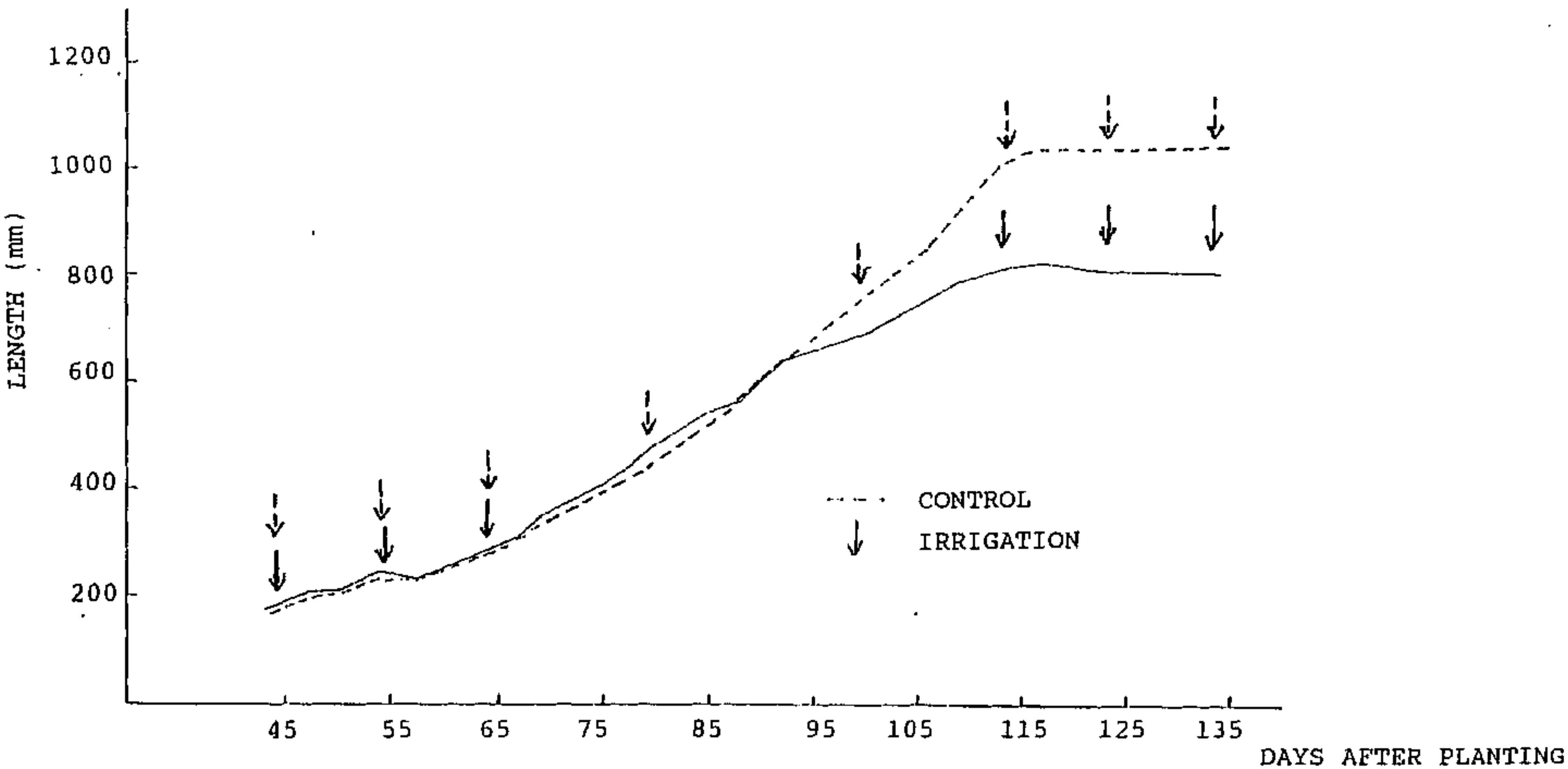


APPENDIX 3.1.20 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D12a (1987 SEASON)

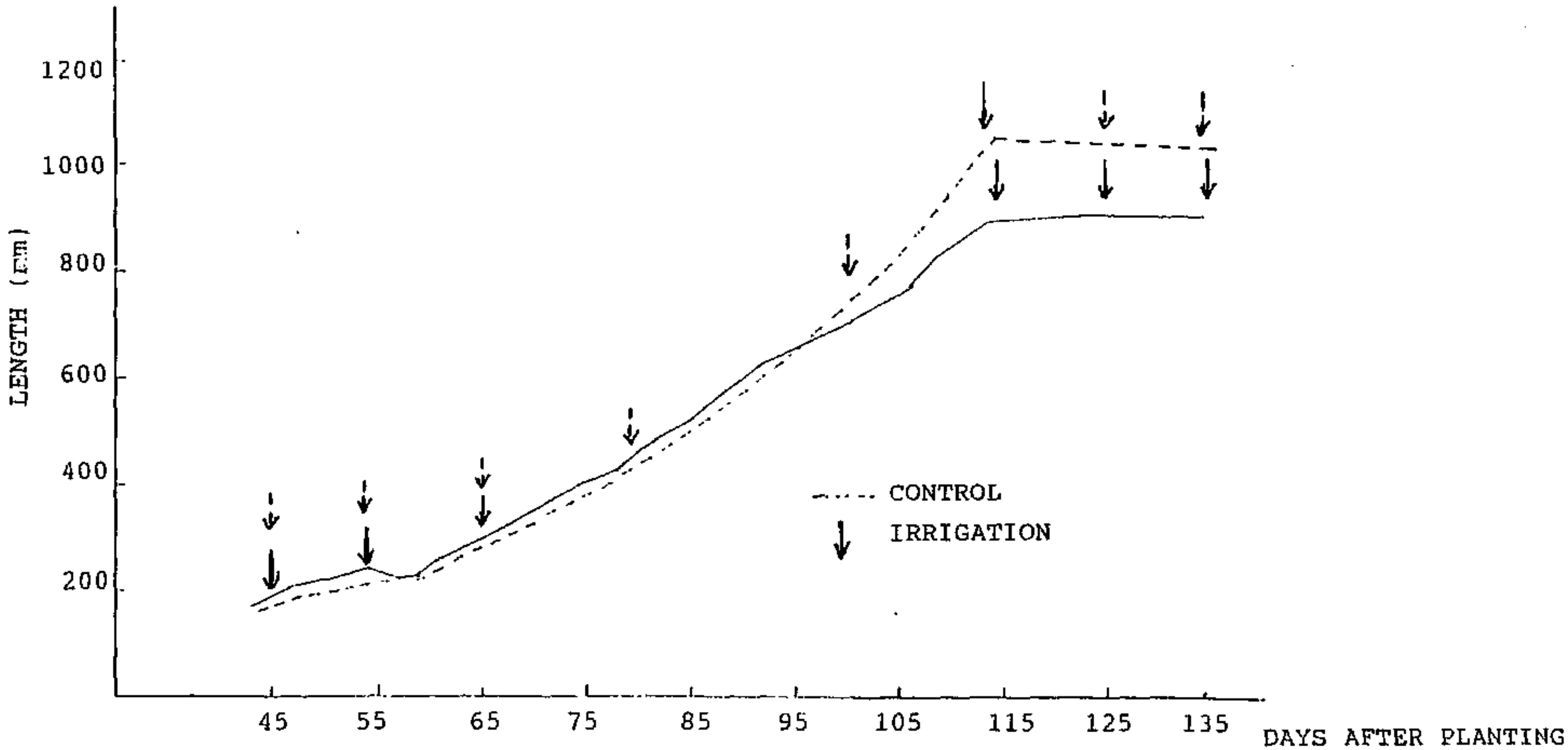
a 3.1



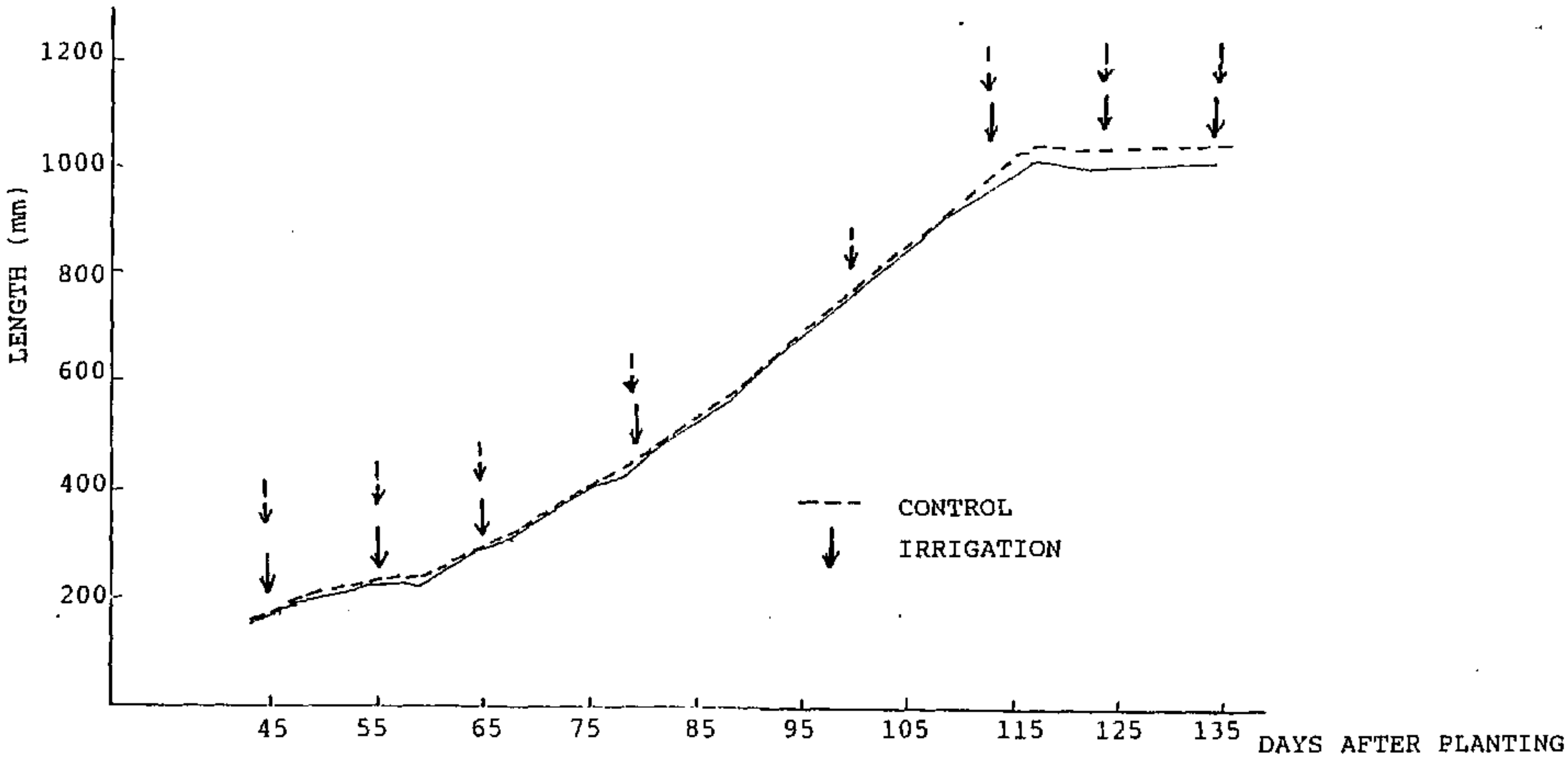
APPENDIX 3.1.21 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D16a (1987 SEASON)



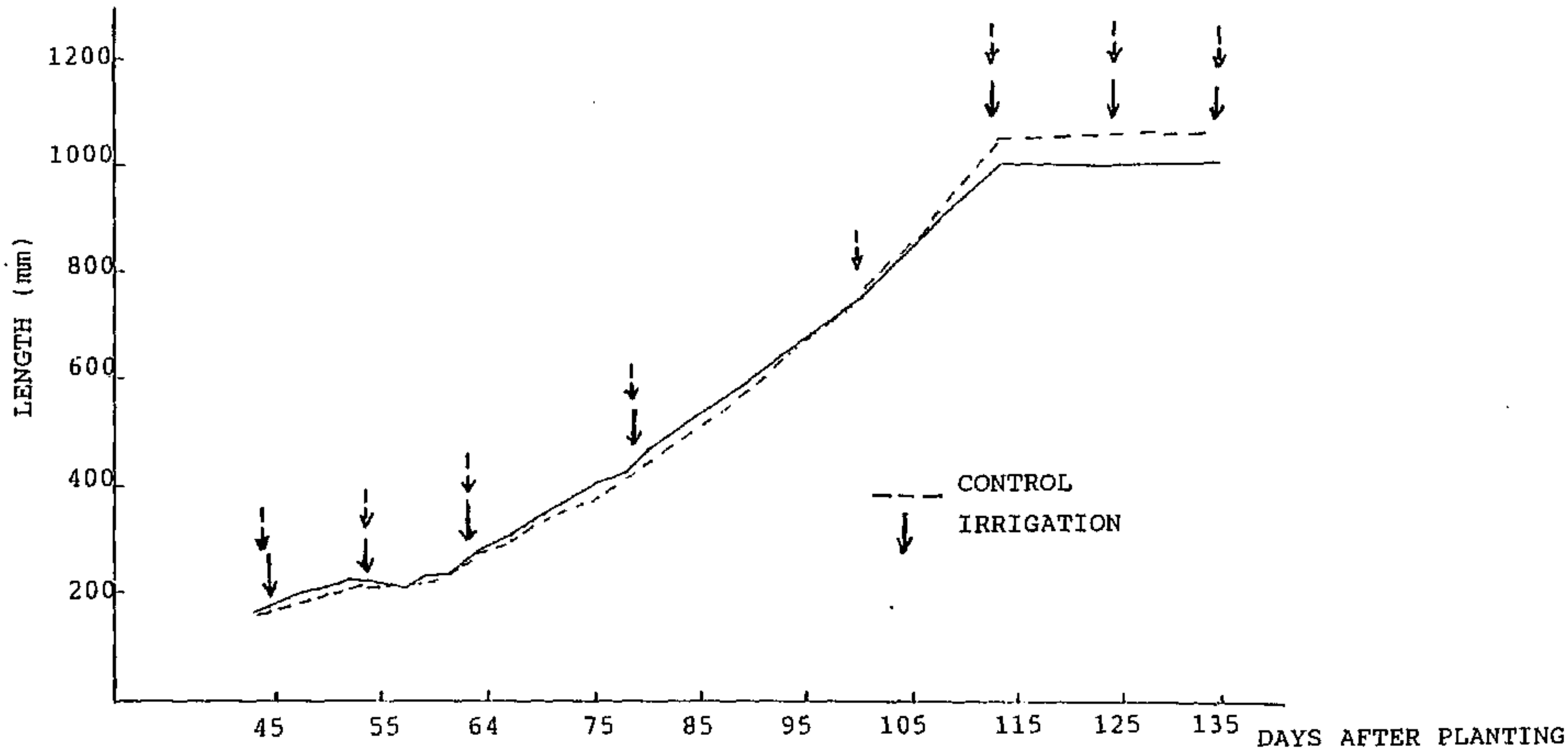
APPENDIX 3.1.22 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D12b (1987 SEASON)



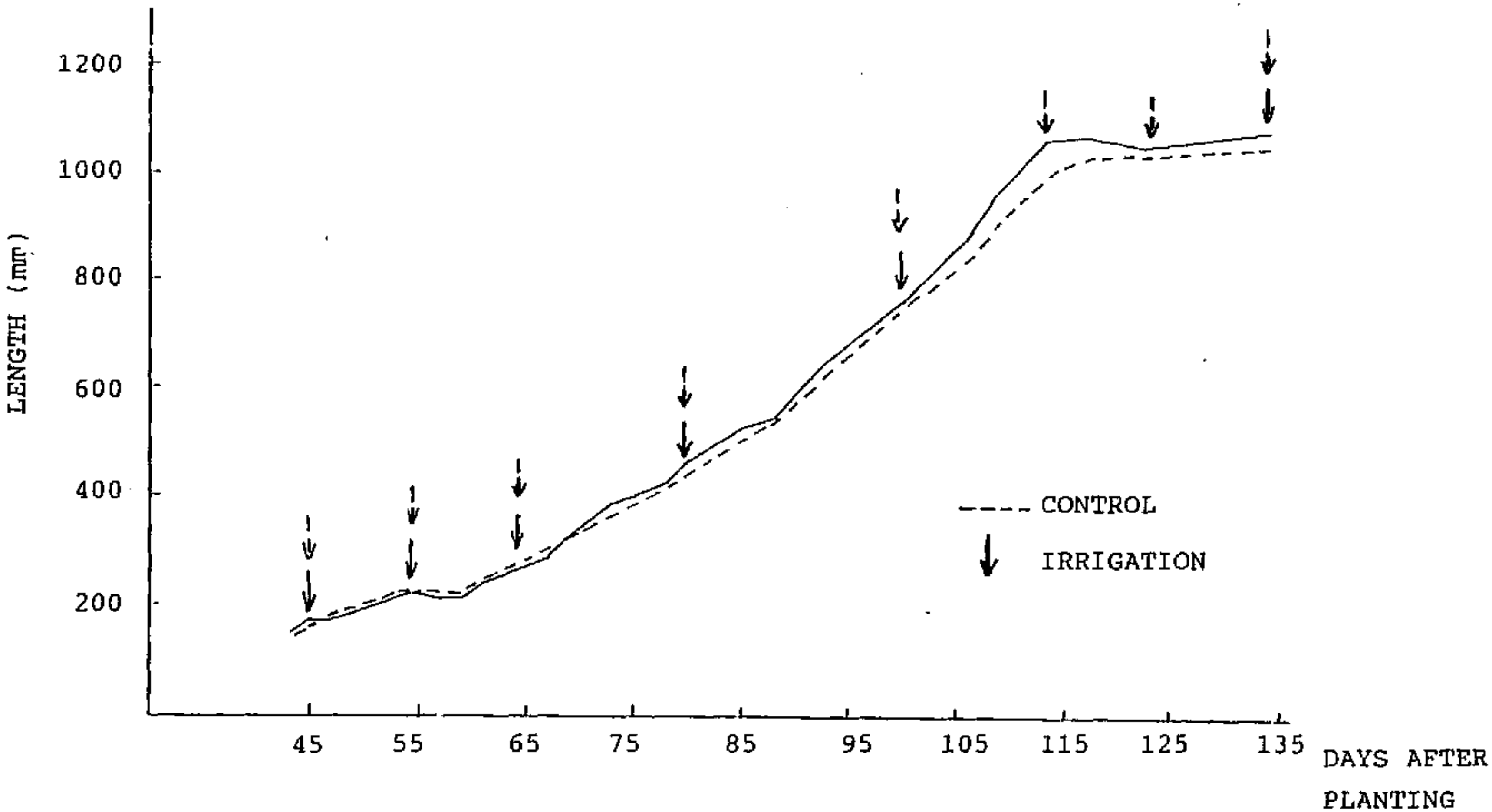
APPENDIX 3.1.23 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D16b (1987 SEASON)



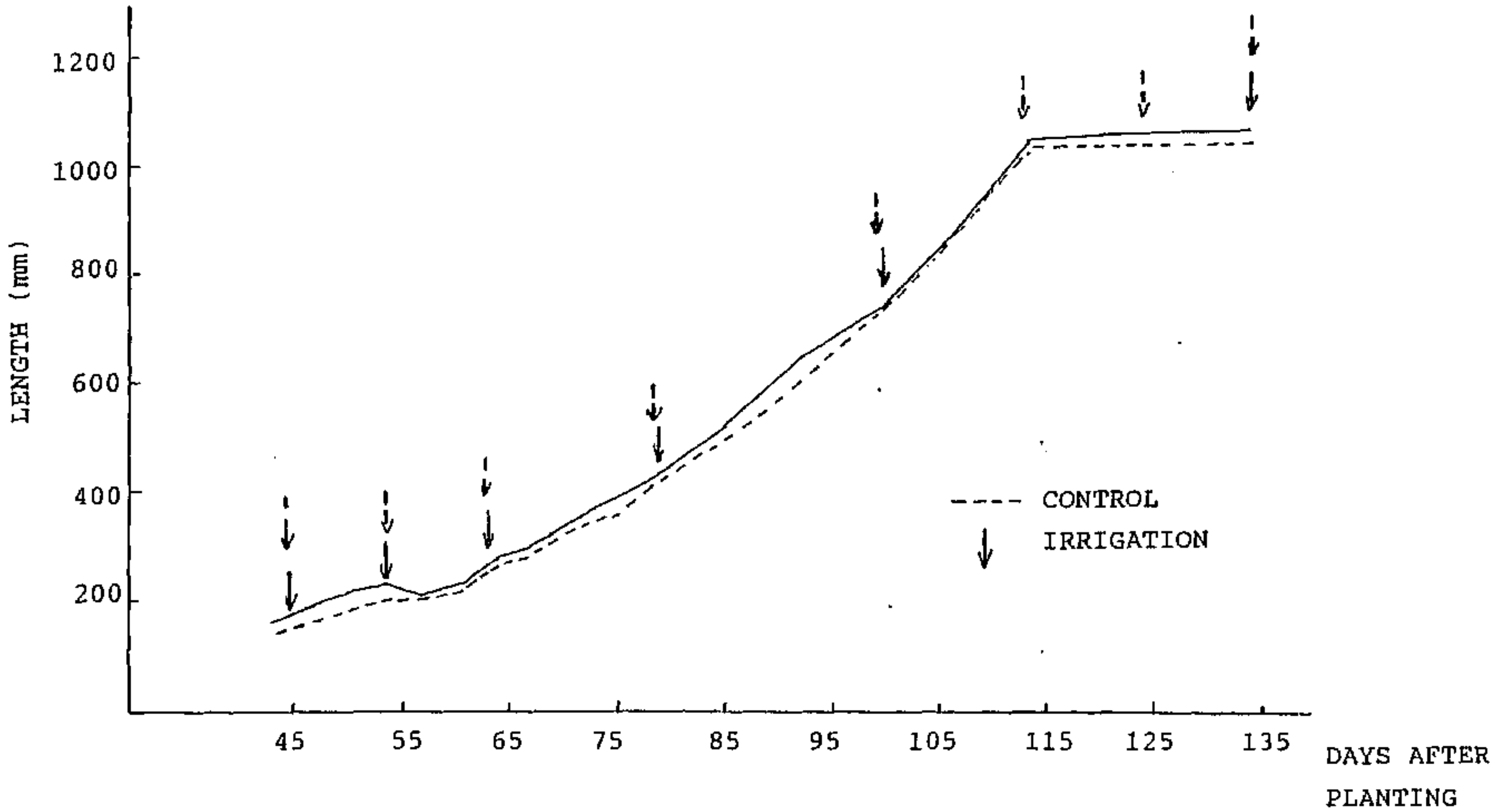
APPENDIX 3.1.24 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D12c (1987 SEASON)



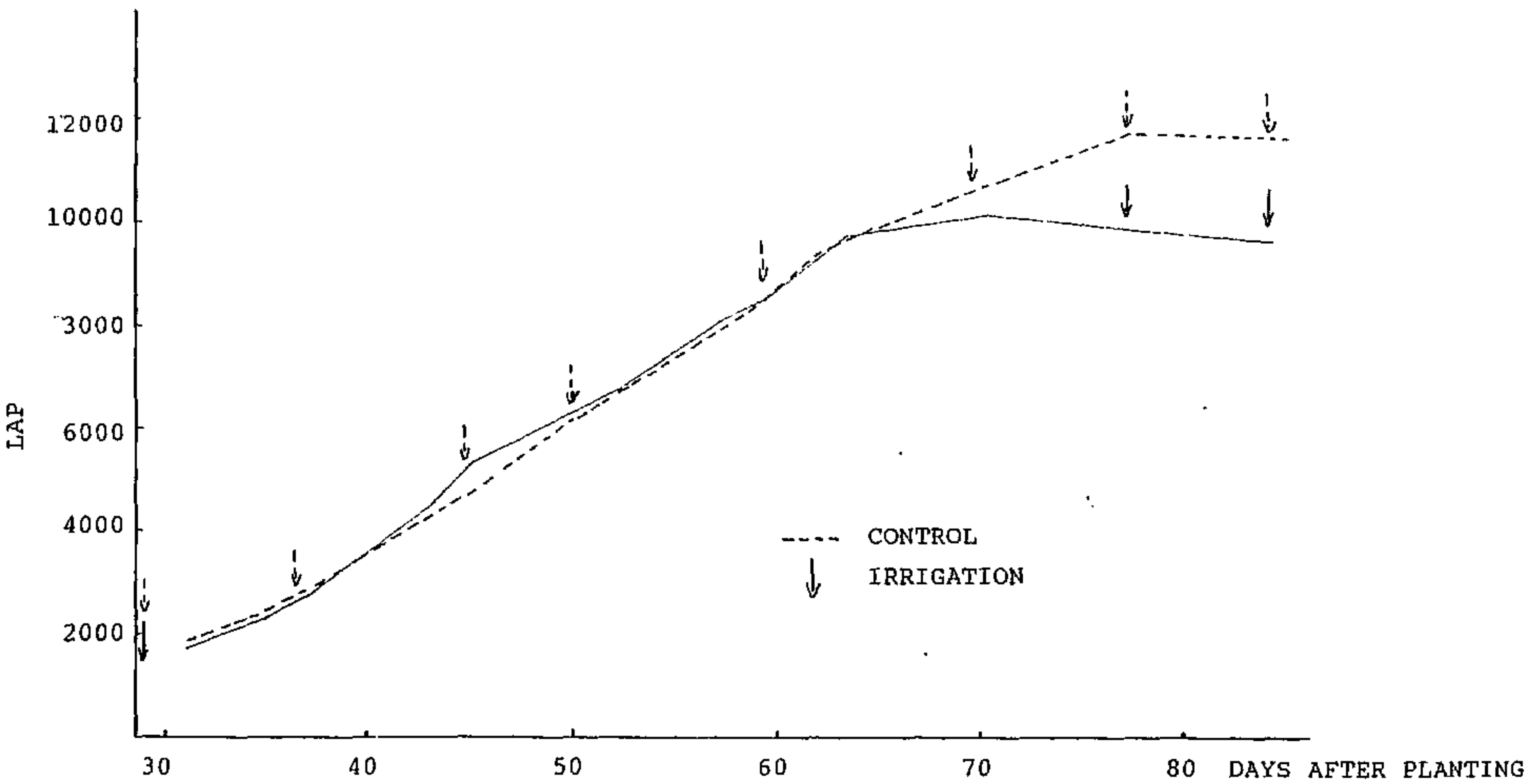
APPENDIX 3.1.25 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D16c (1987 SEASON)



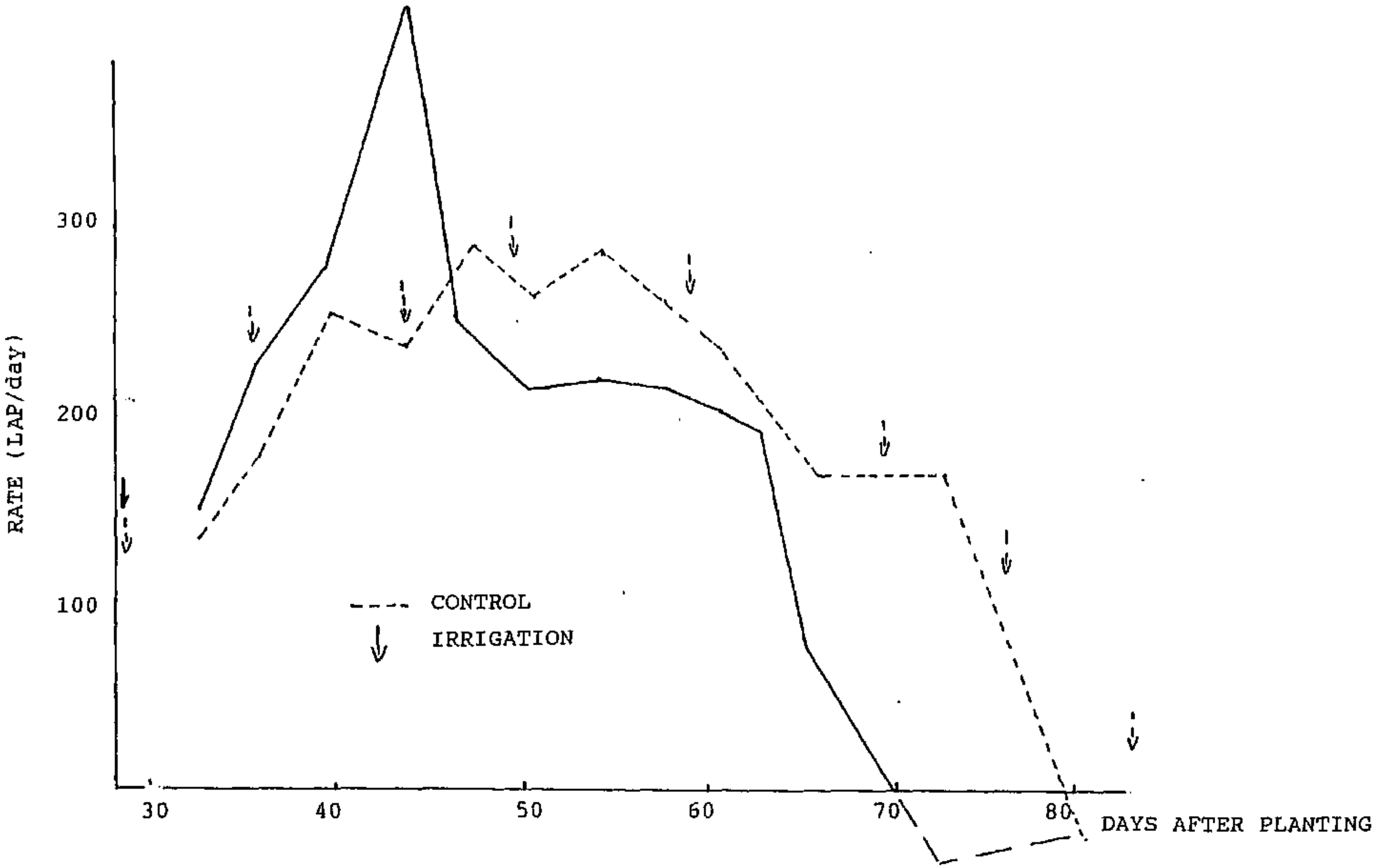
APPENDIX 3.1.26 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D12 f (1987 SEASON)



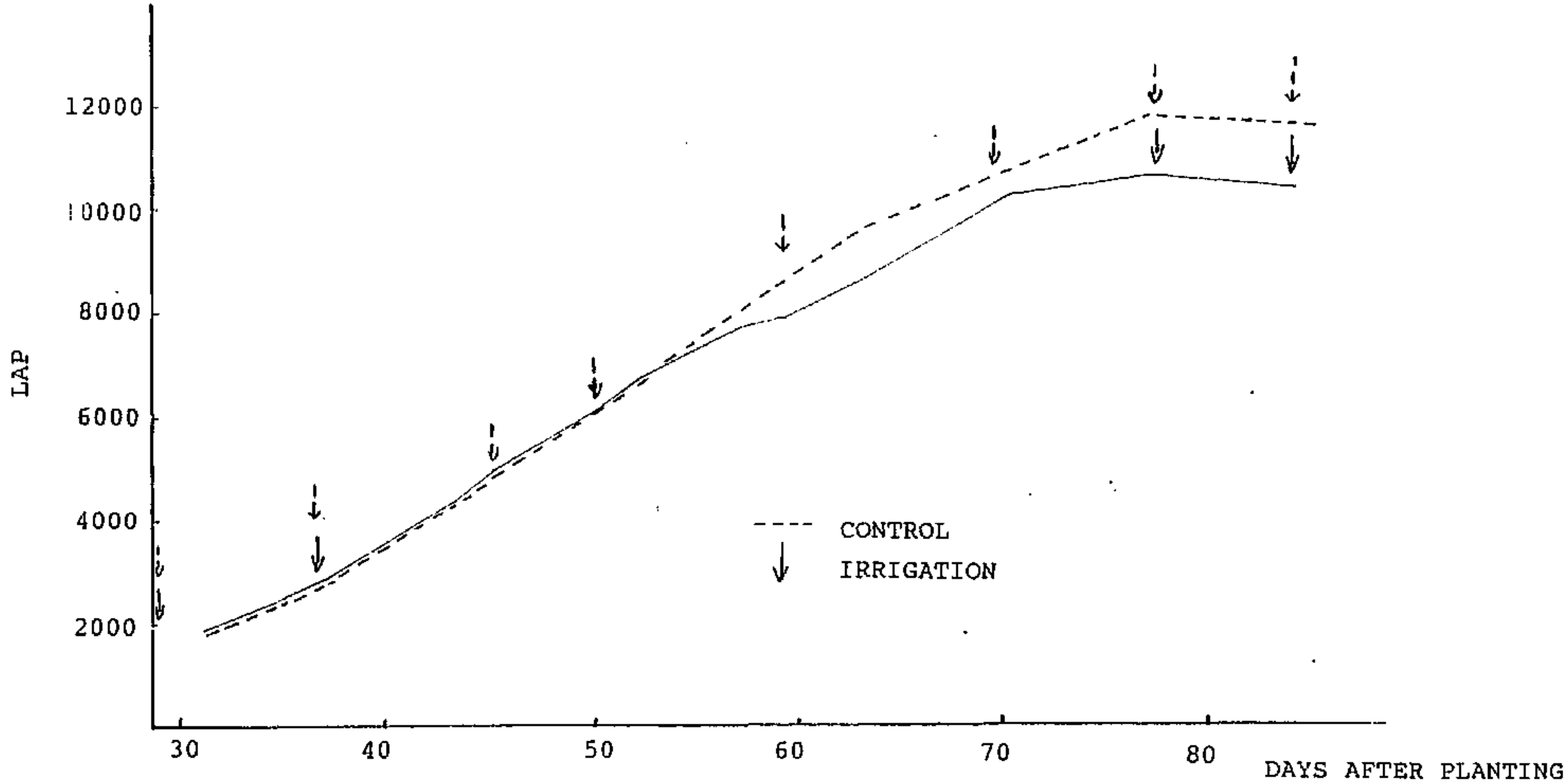
APPENDIX 3.1.27 CUMULATIVE STEM ELONGATION OF DURUM WHEAT ON PLOT D16 f (1987 SEASON)



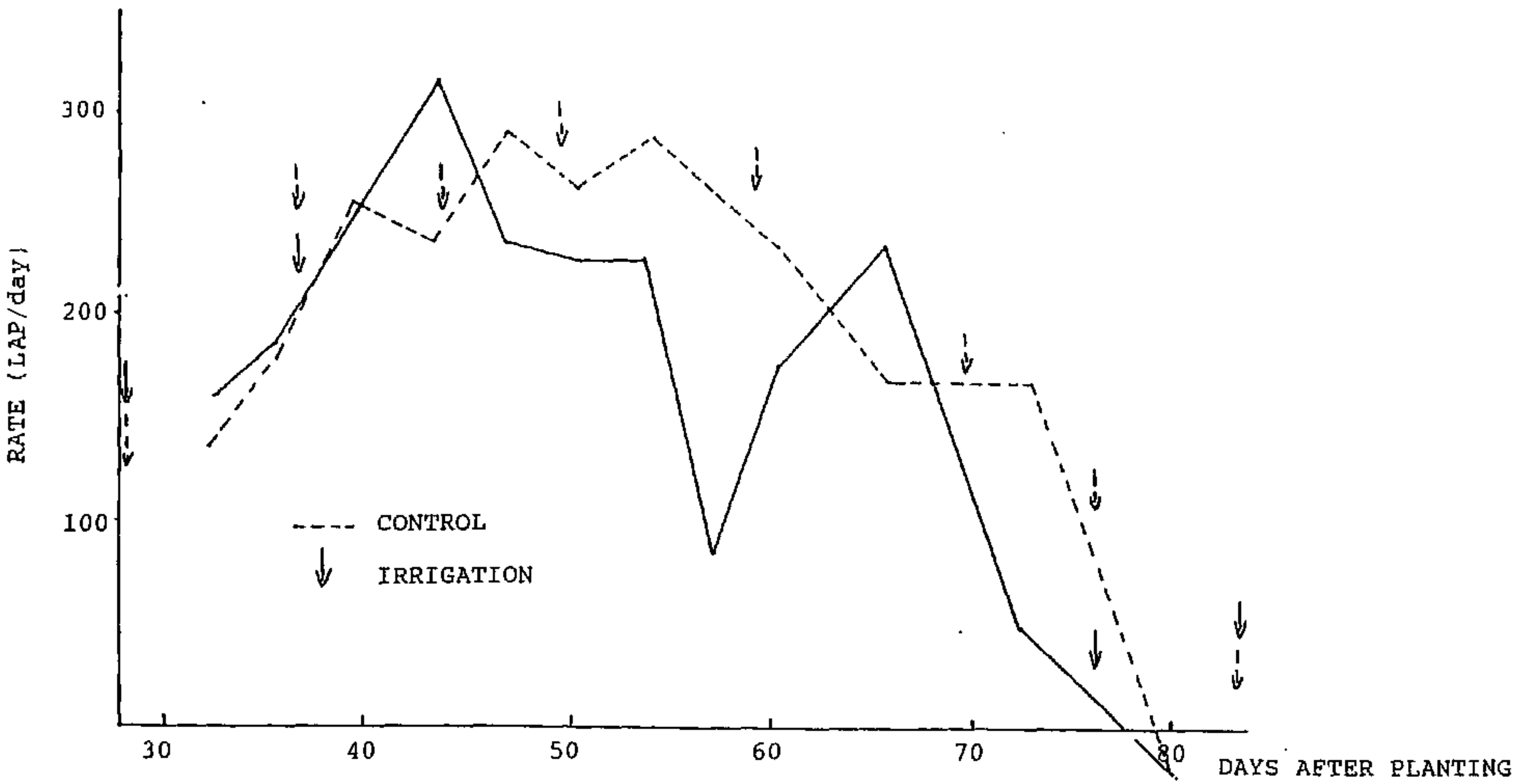
APPENDIX 3.1.28 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT D12a (1986-1987 SEASON)



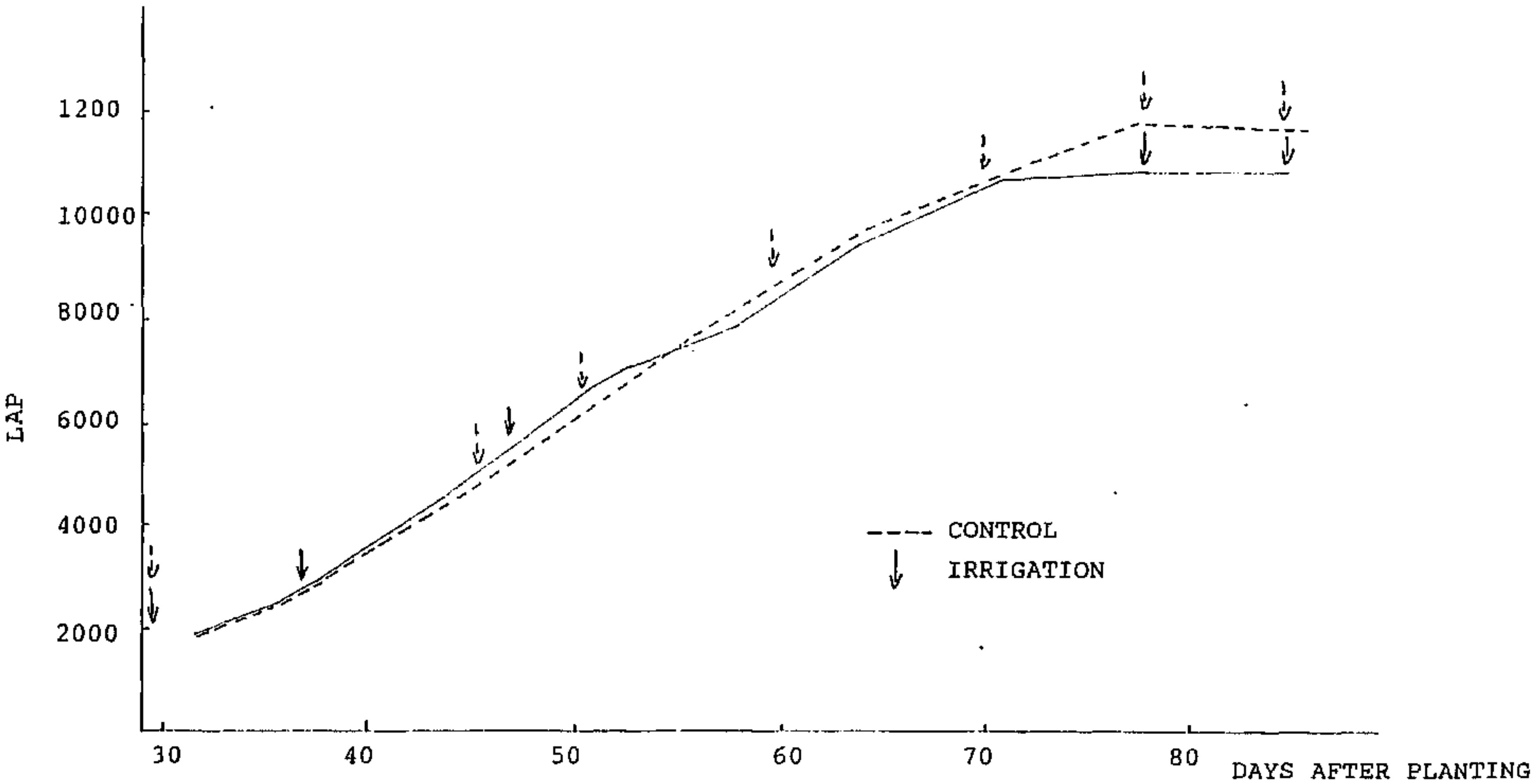
APPENDIX 3.1.29 LEAF EXPANSION RATE OF MAIZE ON PLOT D12a (1986-1987 SEASON)



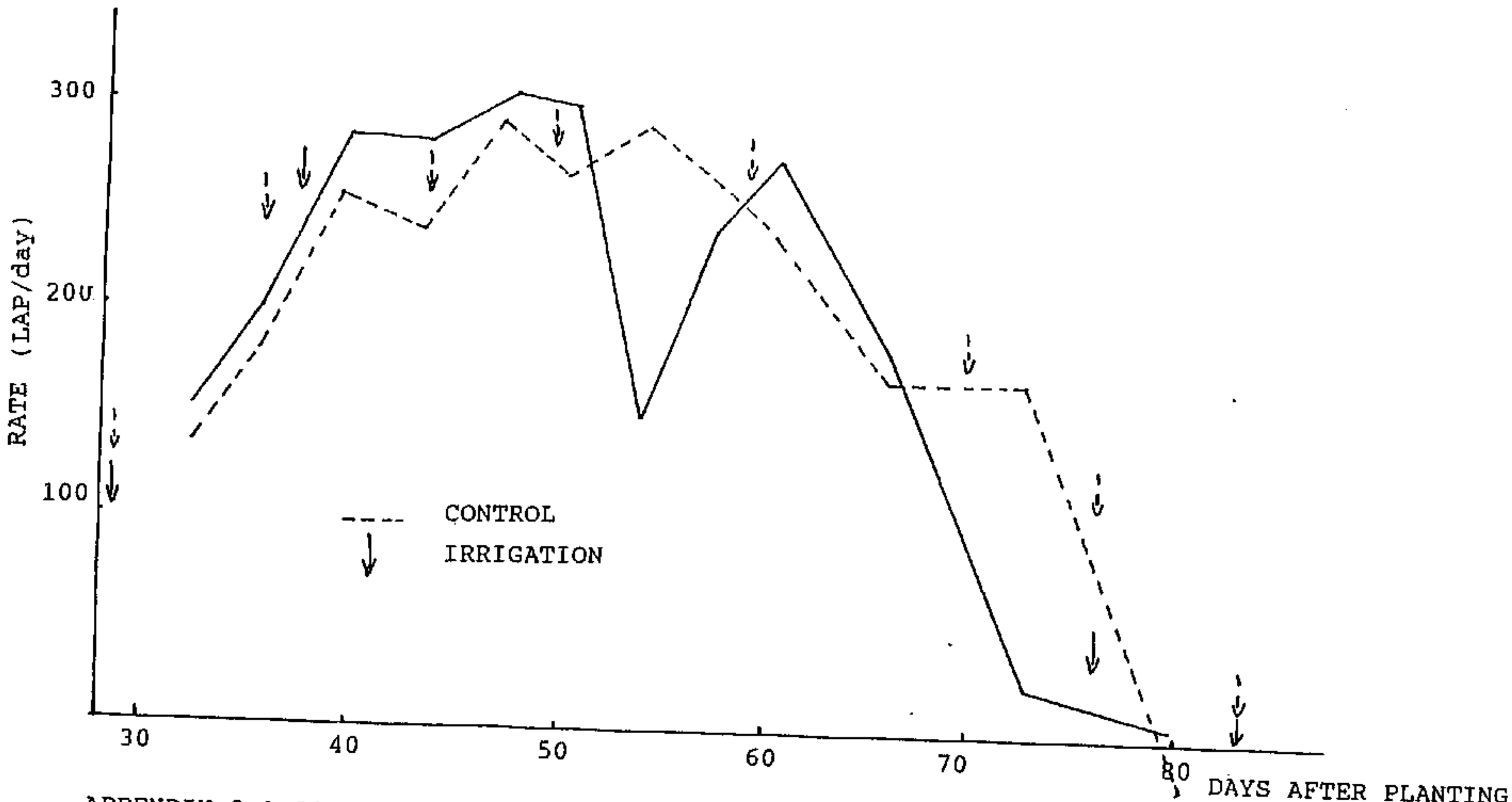
APPENDIX 3.1.30 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOTS D12b (1986-1987 SEASON)



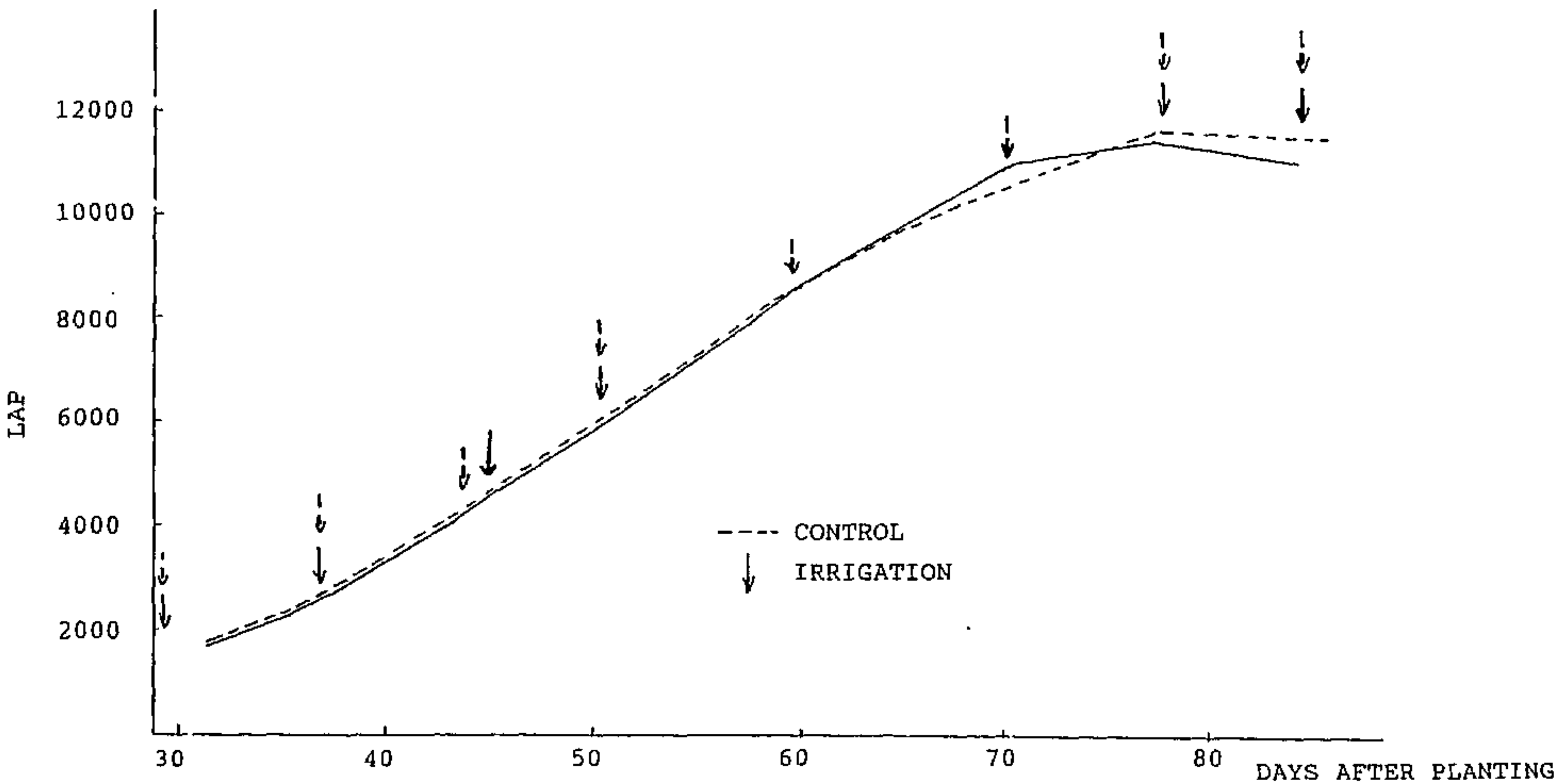
APPENDIX 3.1.31 LEAF EXPANSION RATE OF MAIZE ON PLOT D12b (1986-1987 SEASON)



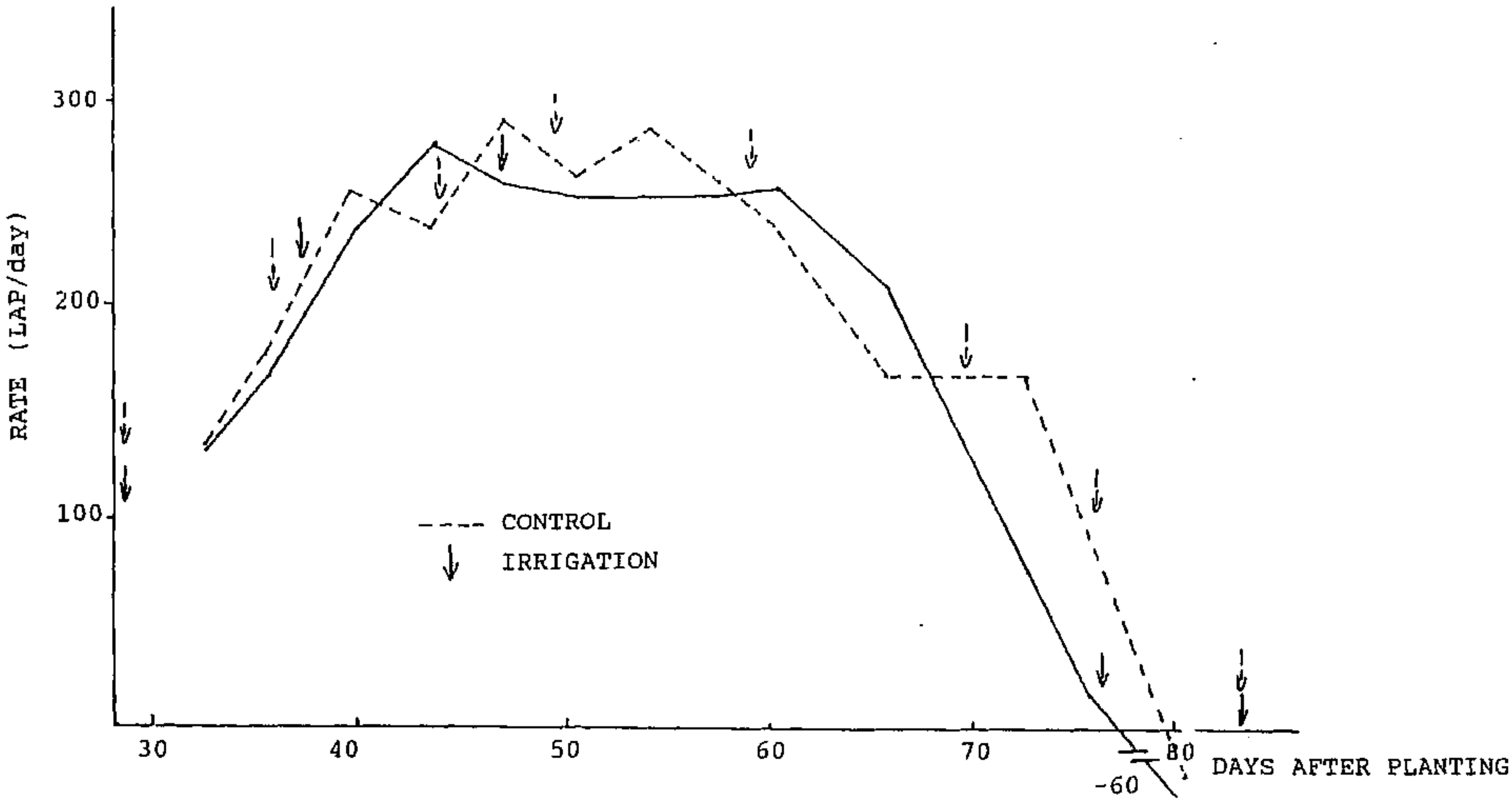
APPENDIX 3.1.32 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT D12c (1986-1987 SEASON)



APPENDIX 3.1.33 LEAF EXPANSION RATE OF MAIZE ON PLOT D12c (1986-1987 SEASON)

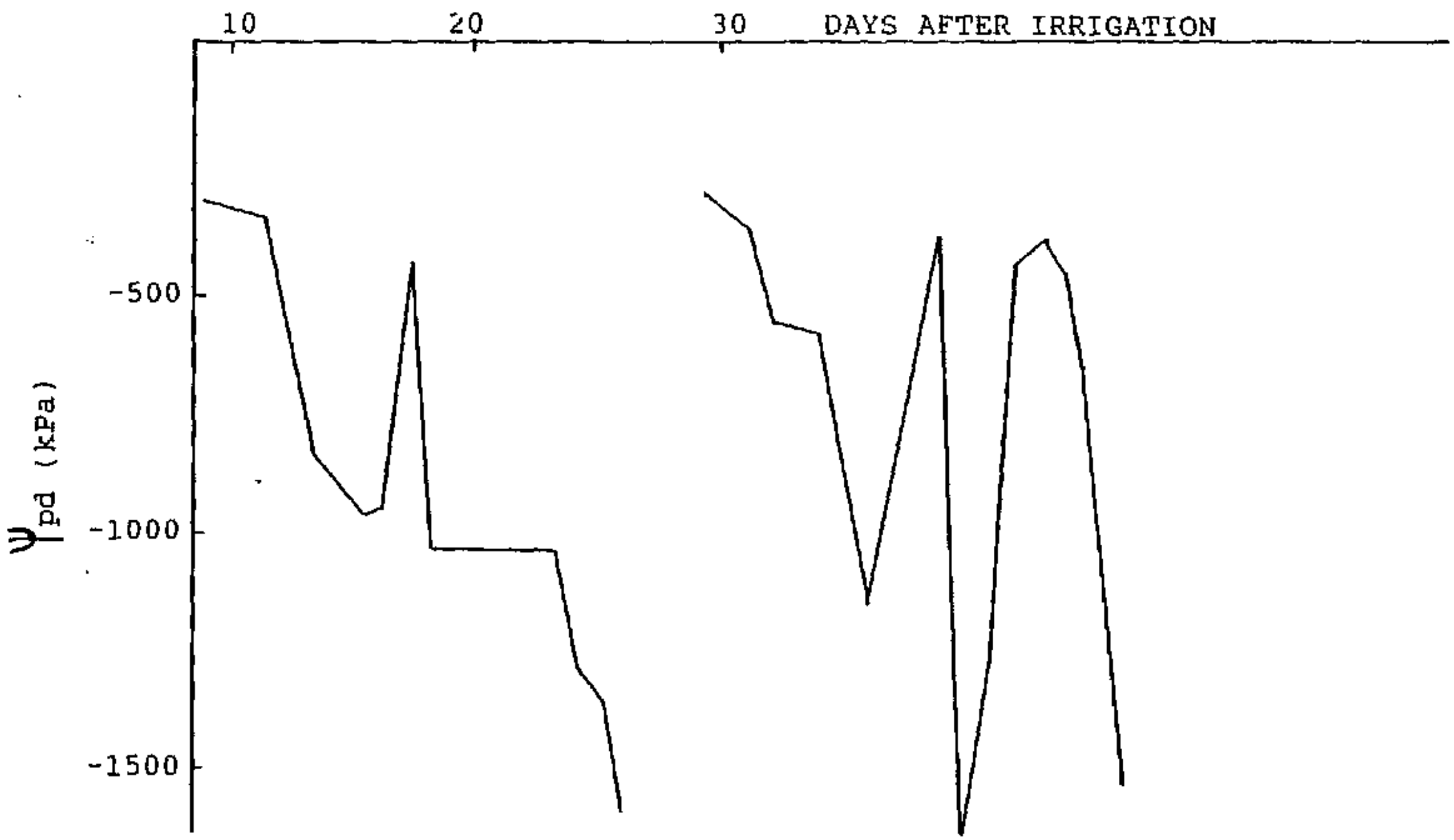


APPENDIX 3.1.34 CUMULATIVE LEAF EXPANSION OF MAIZE ON PLOT D12d (1986-1987 SEASON)

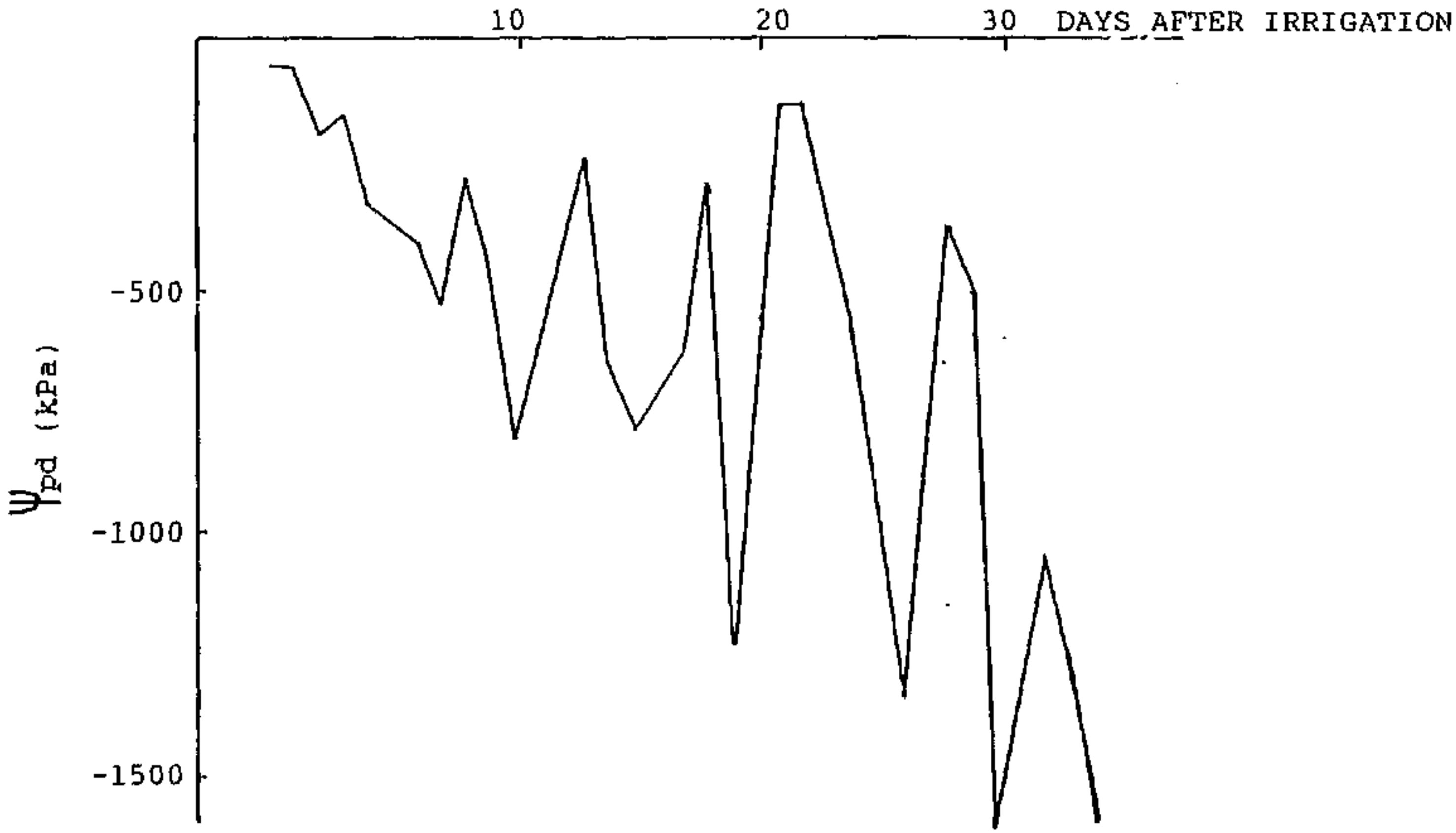


APPENDIX 3.1.35 LEAF EXPANSION RATE OF MAIZE ON PLOT D12d (1986-1987 SEASON)

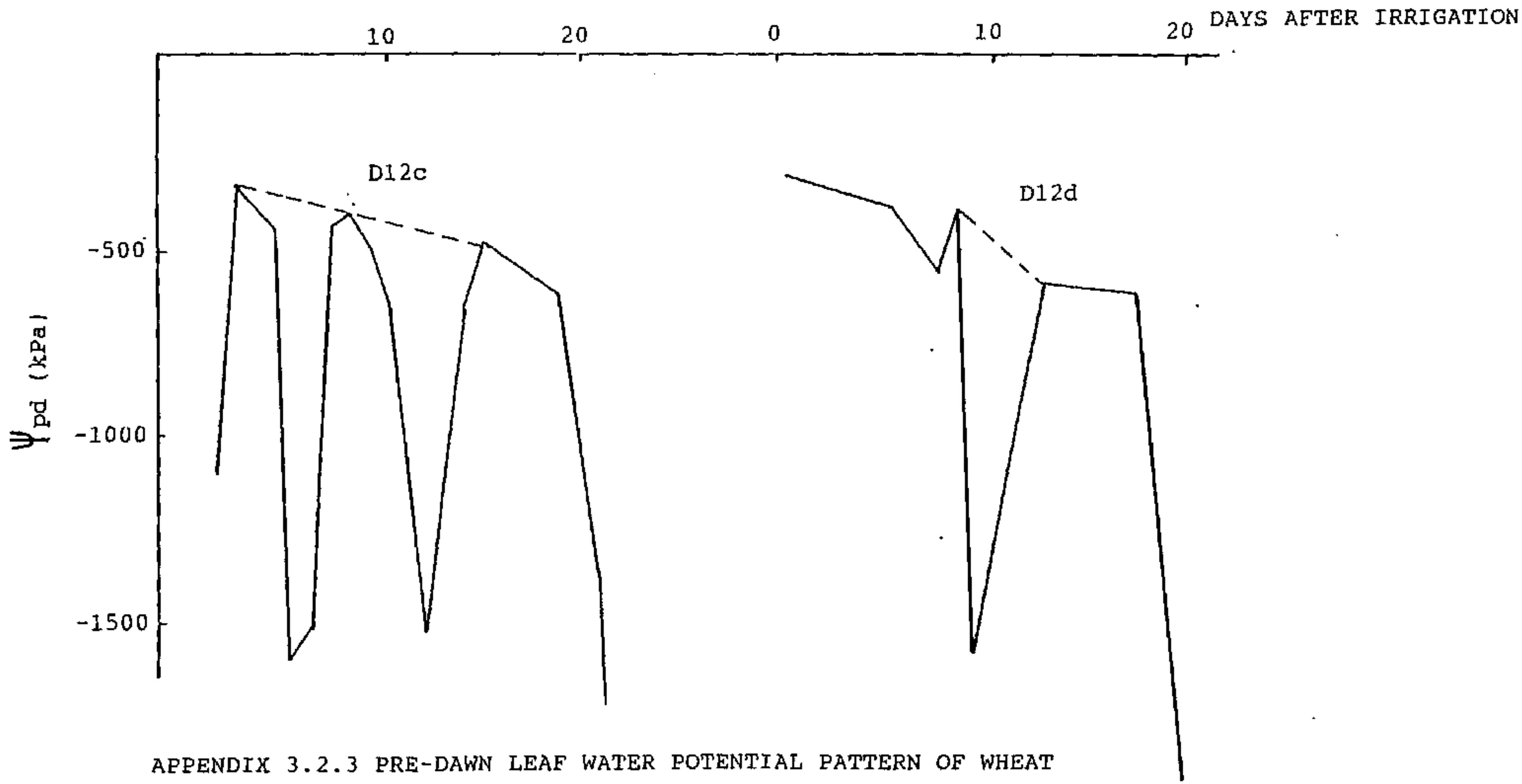
a 3.1



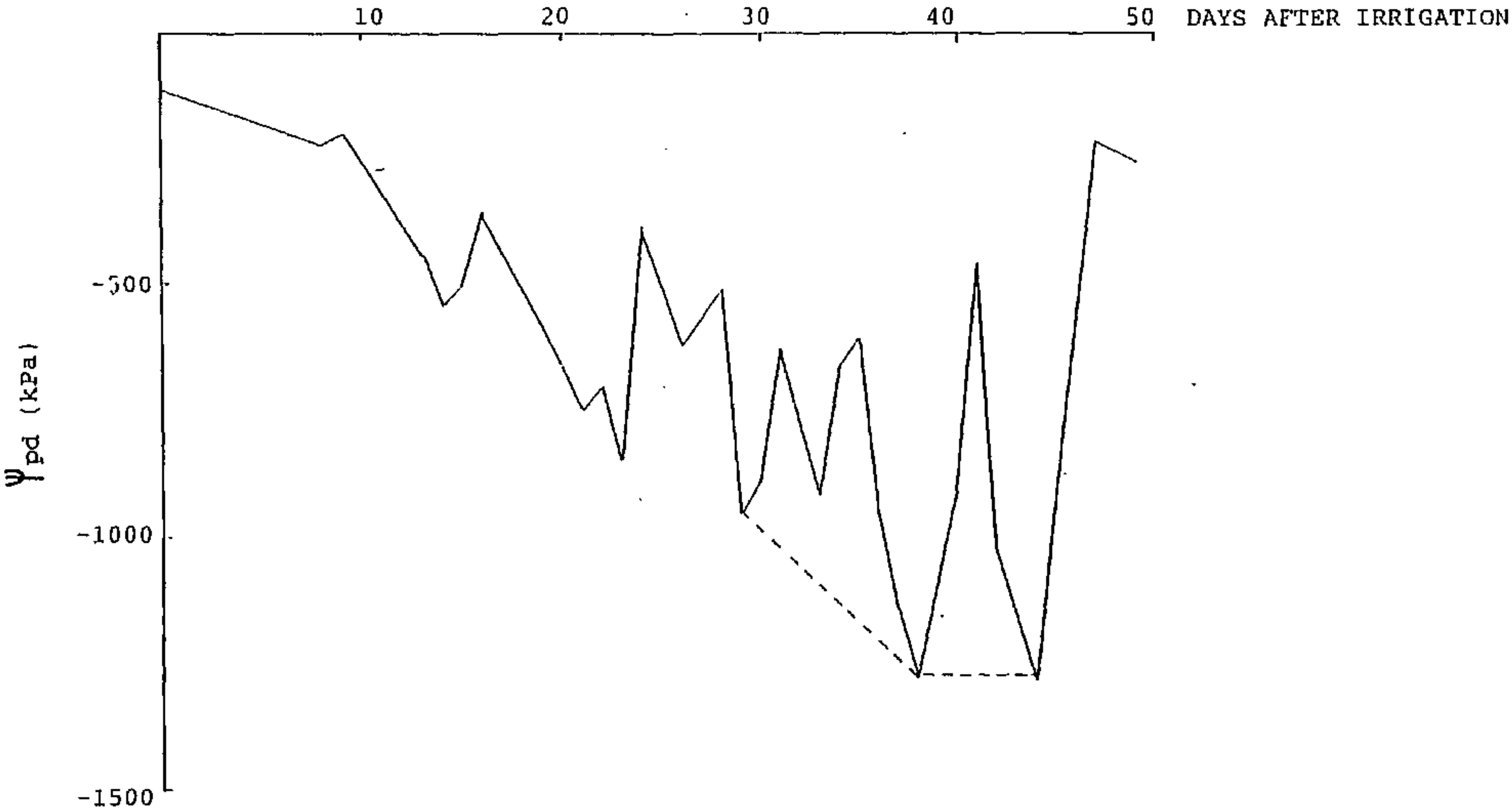
APPENDIX 3.2.1 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D12a (1985 SEASON)



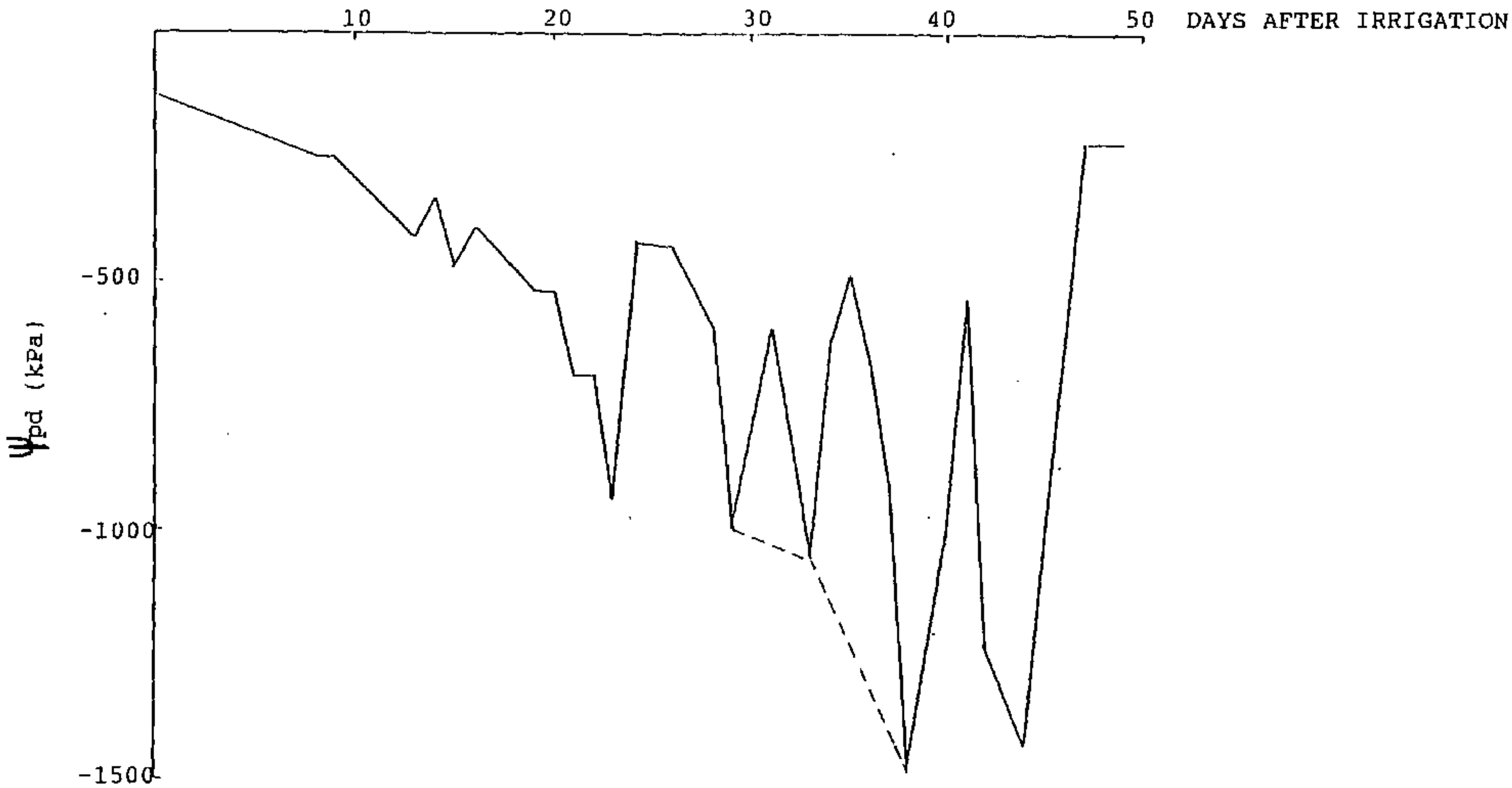
APPENDIX 3.2.2 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D12b (1985 SEASON)



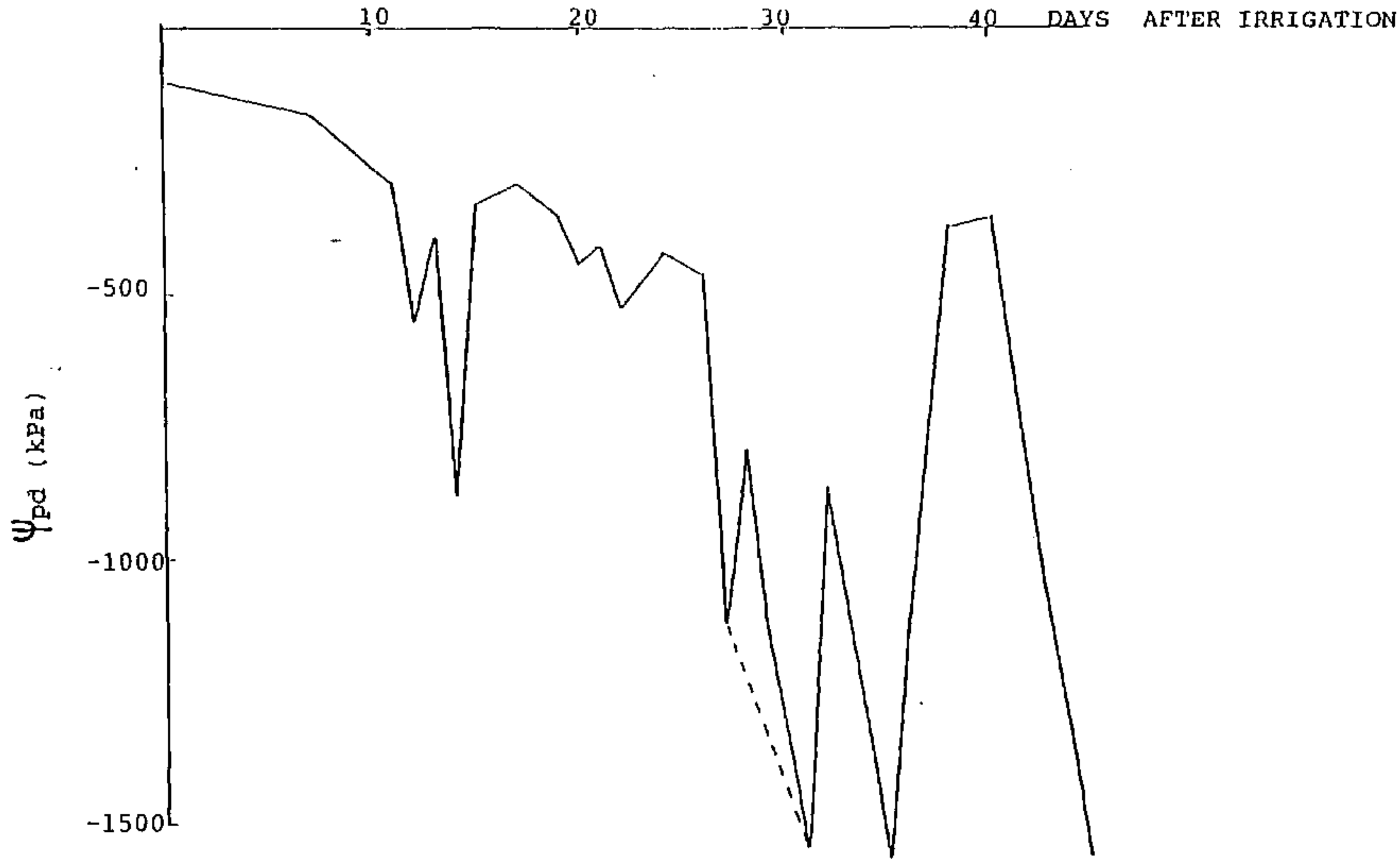
APPENDIX 3.2.3 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOTS D12c (1985 SEASON)



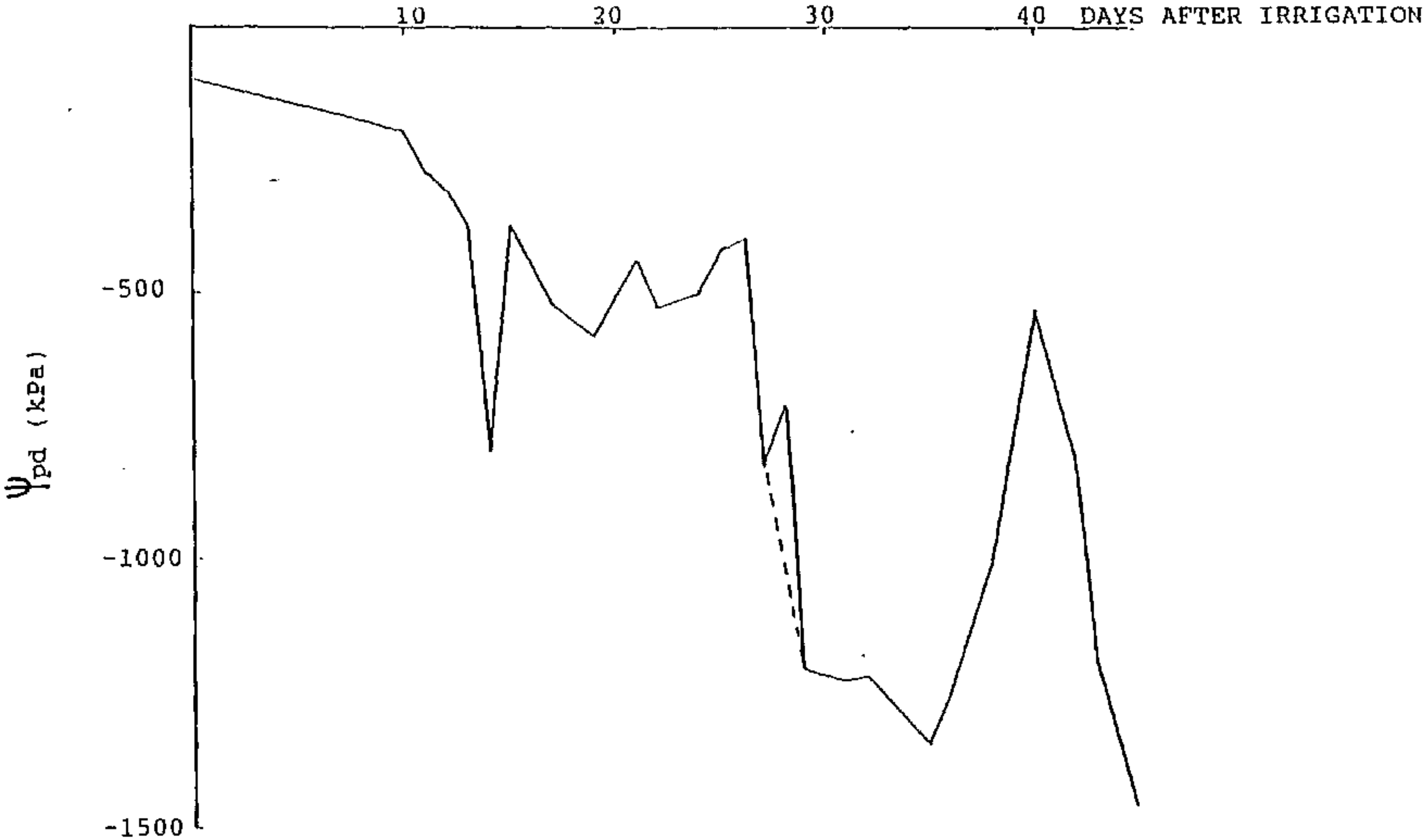
APPENDIX 3.2.4 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D12a (1986 SEASON)



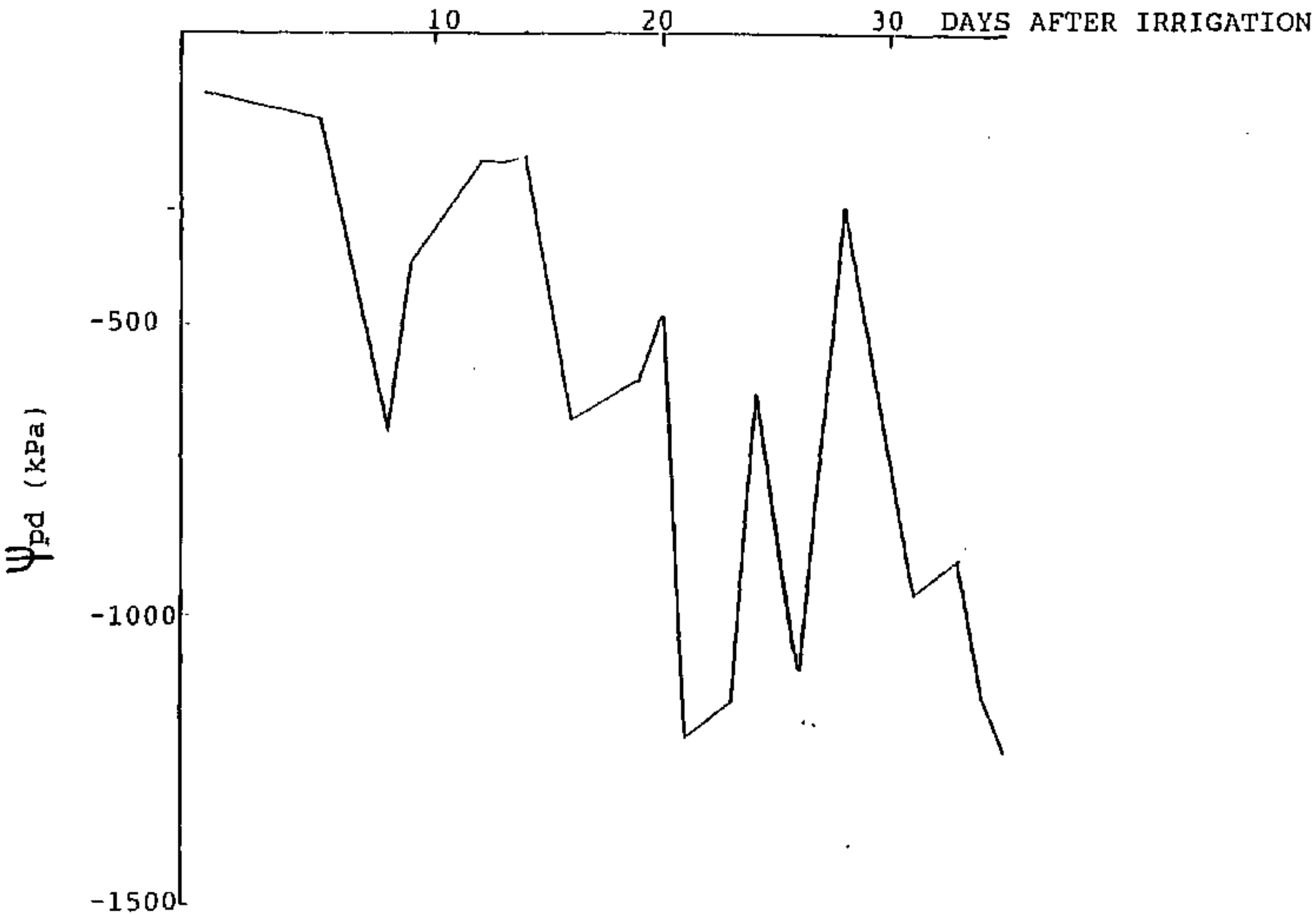
APPENDIX 3.2.5 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D16a (1986 SEASON)



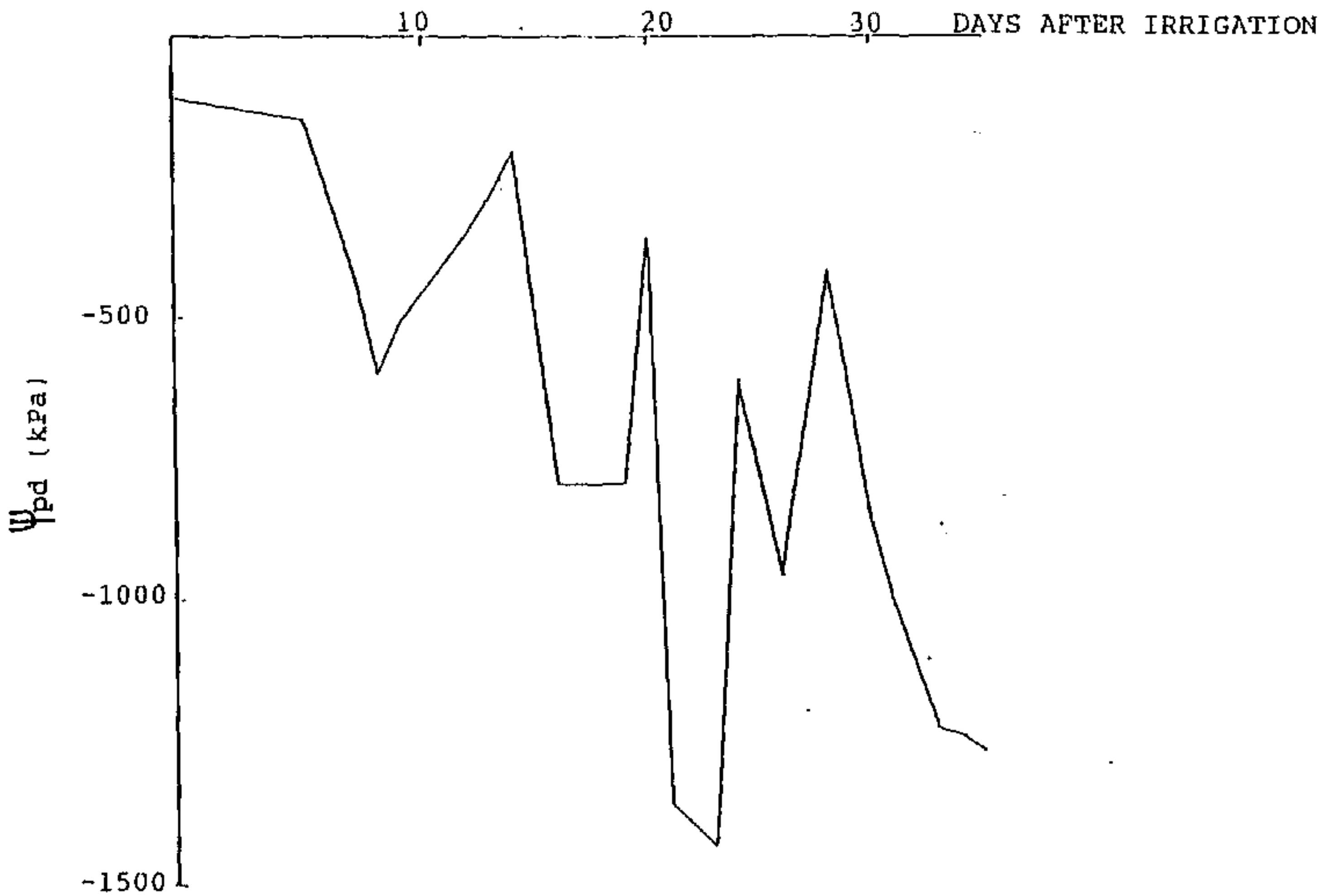
APPENDIX 3.2.6 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D12b (1986 SEASON)



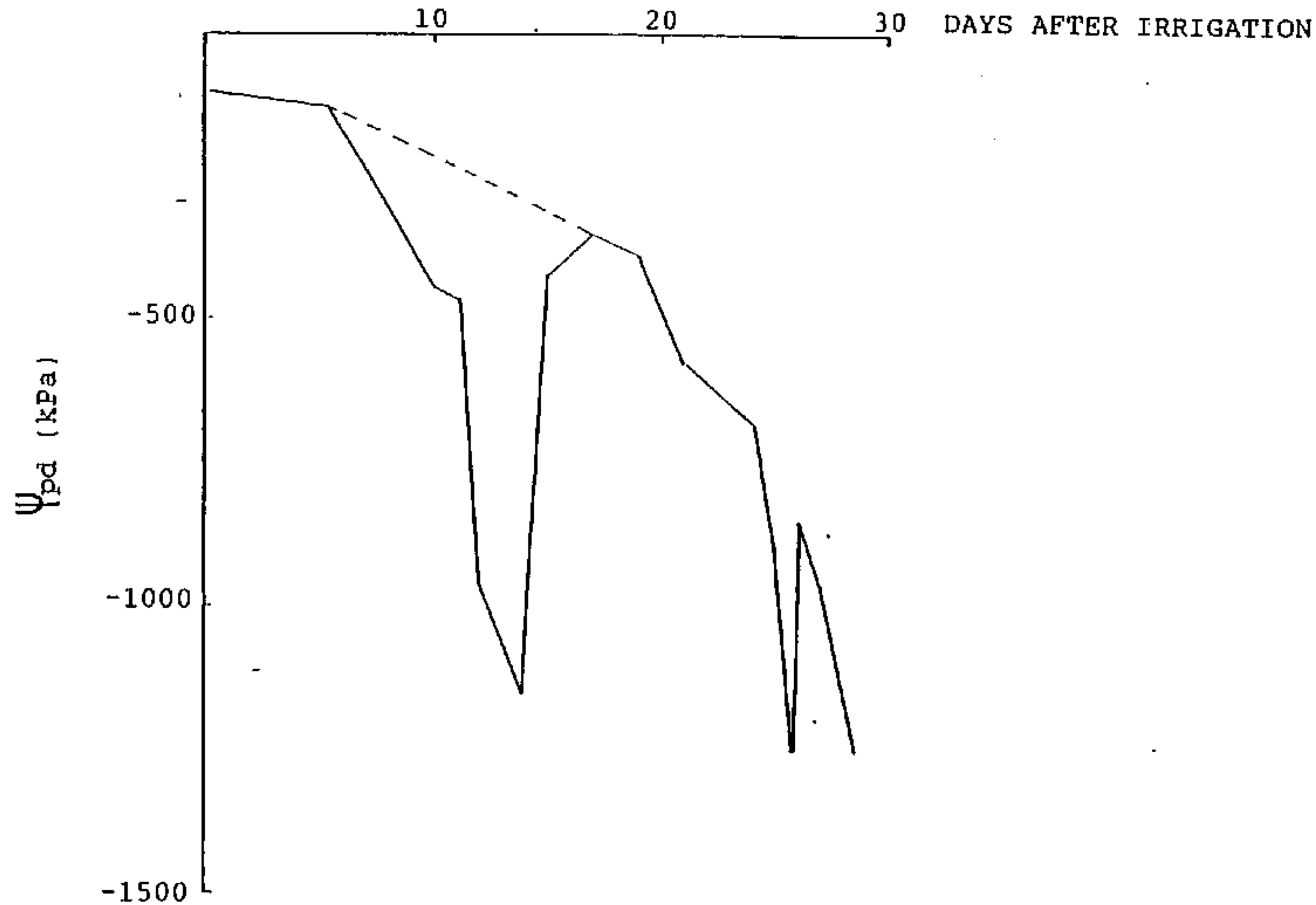
APPENDIX 3.2.7 PRE-DAWN LEAF WATER POTENTIAL OF WHEAT ON PLOT D16b (1986 SEASON)



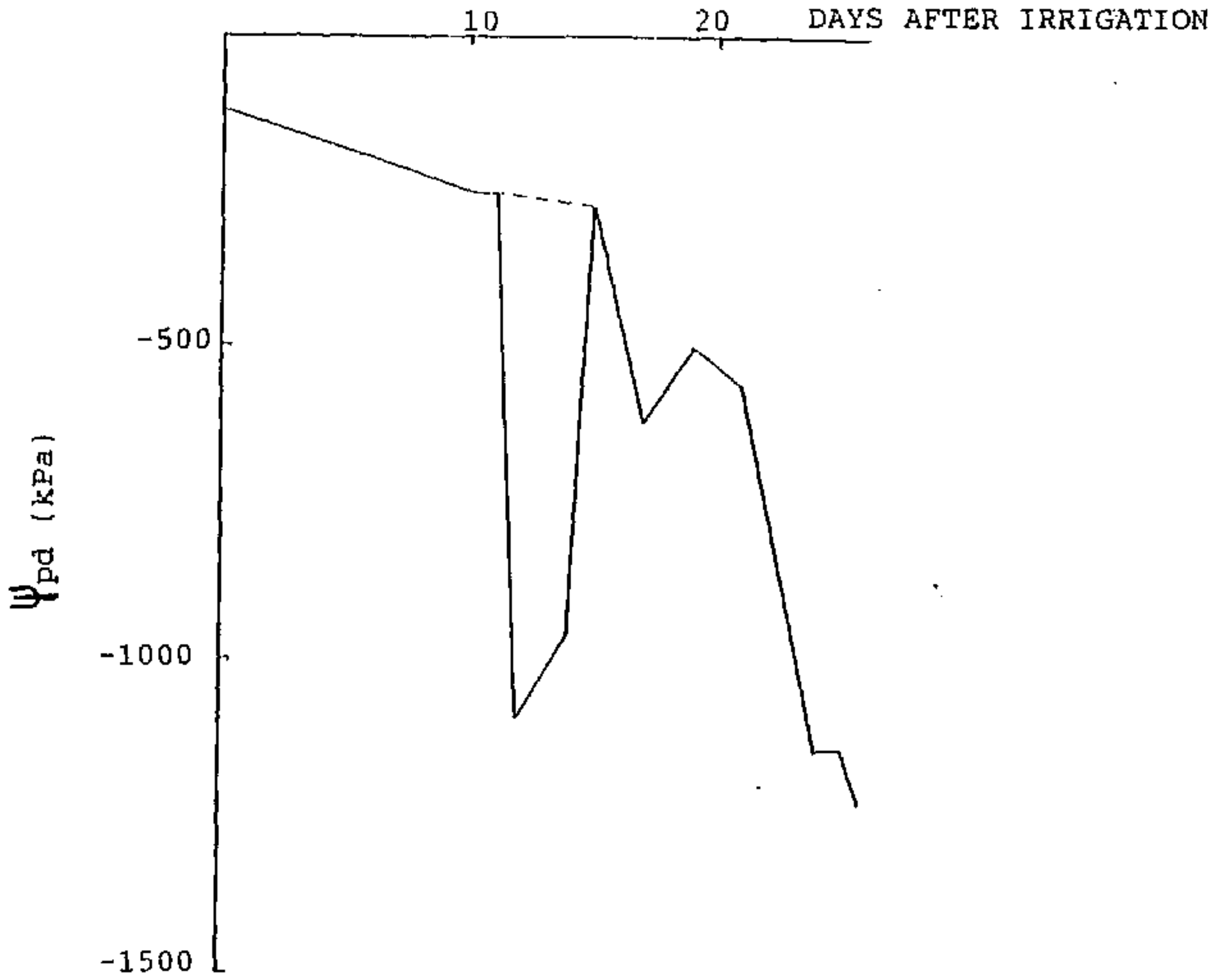
APPENDIX 3.2.8 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D12c
(1986 SEASON)



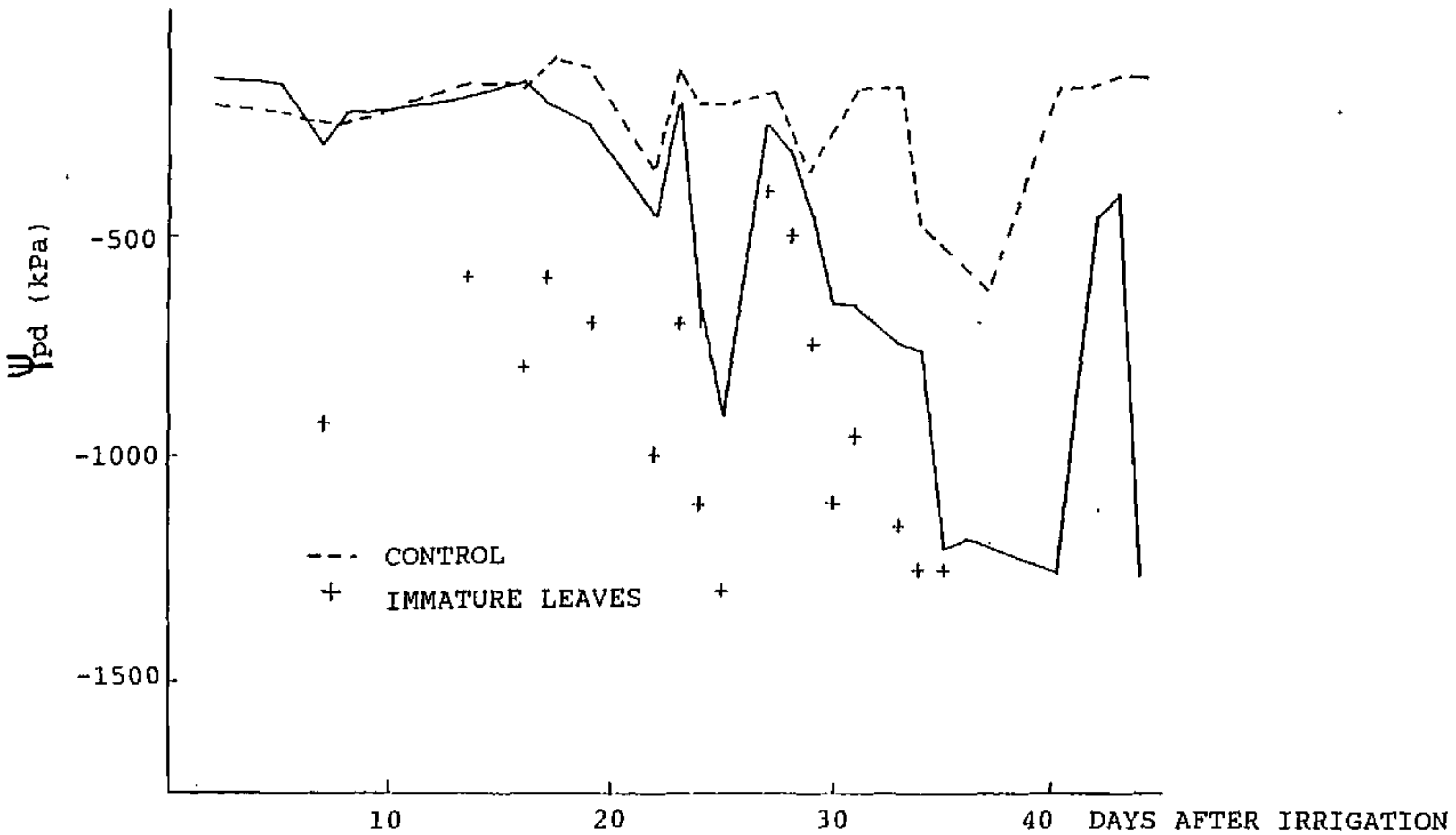
APPENDIX 3.2.9 PRE-DAWN LEAF WATER POTENTIAL OF WHEAT ON PLOT D16c
(1986 SEASON)



APPENDIX 3.2.10 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D12d (1986 SEASON)

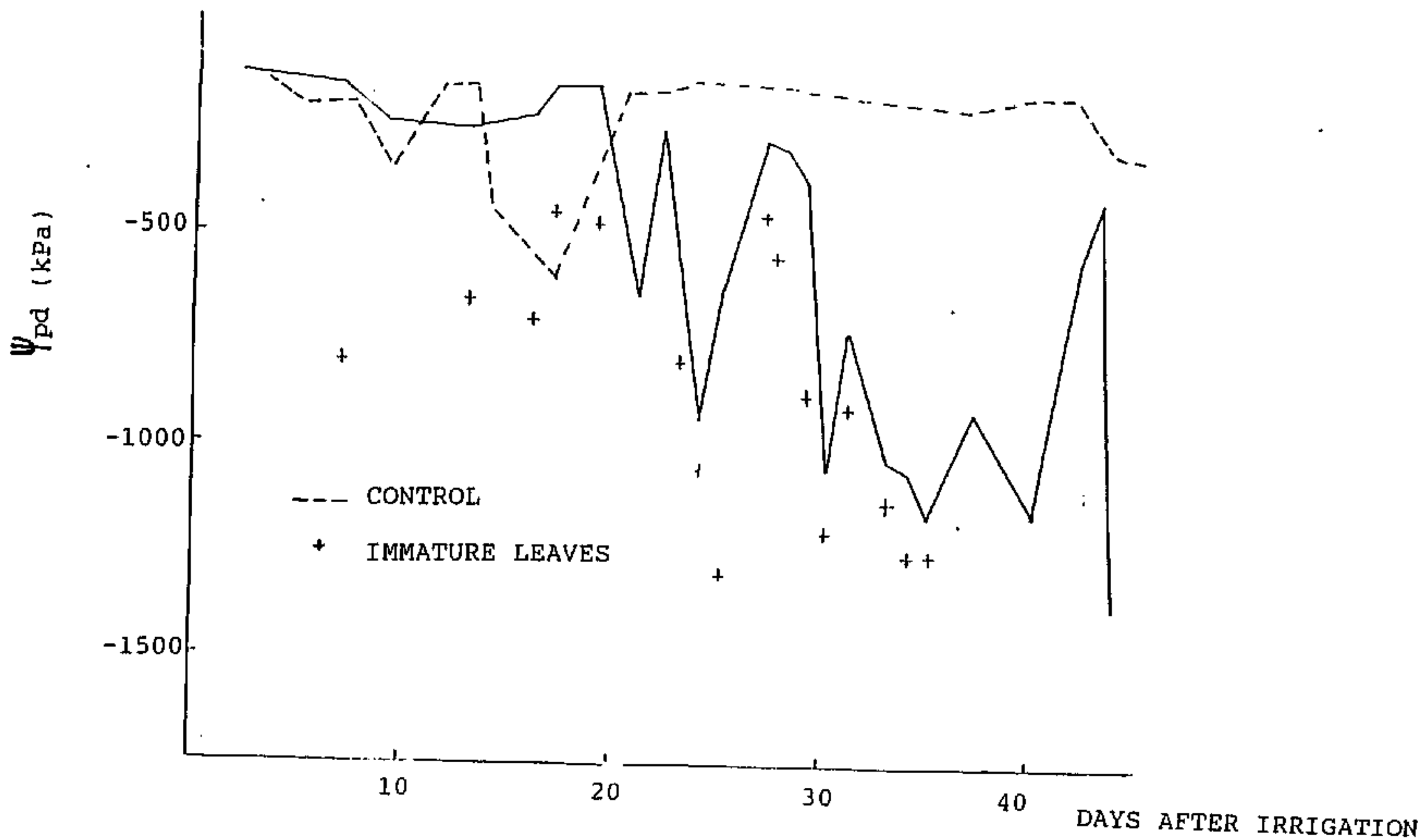


APPENDIX 3.2.11 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF WHEAT ON PLOT D16d (1986 SEASON)

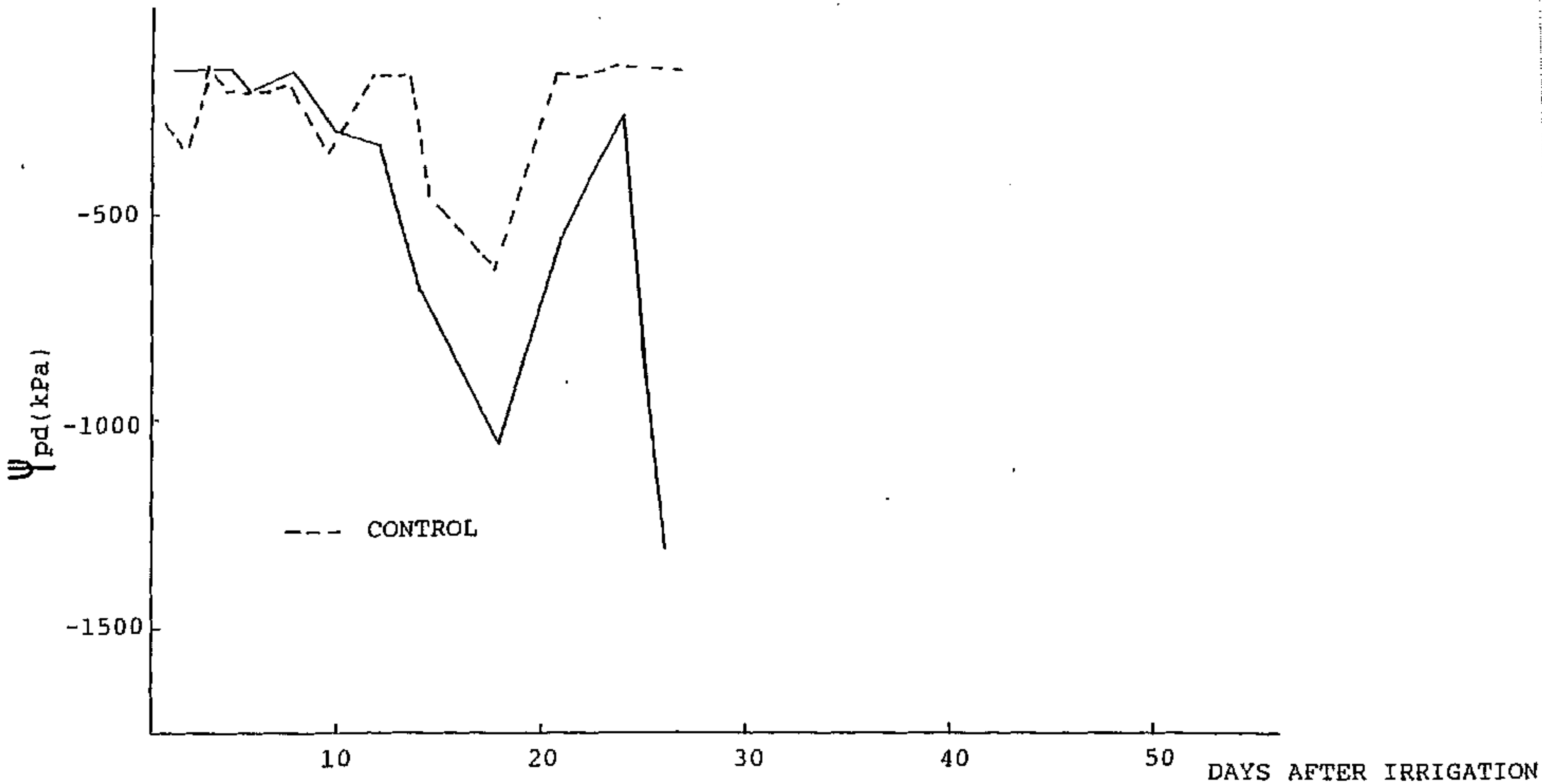


APPENDIX 3.2.12 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D12a
(1987 SEASON)

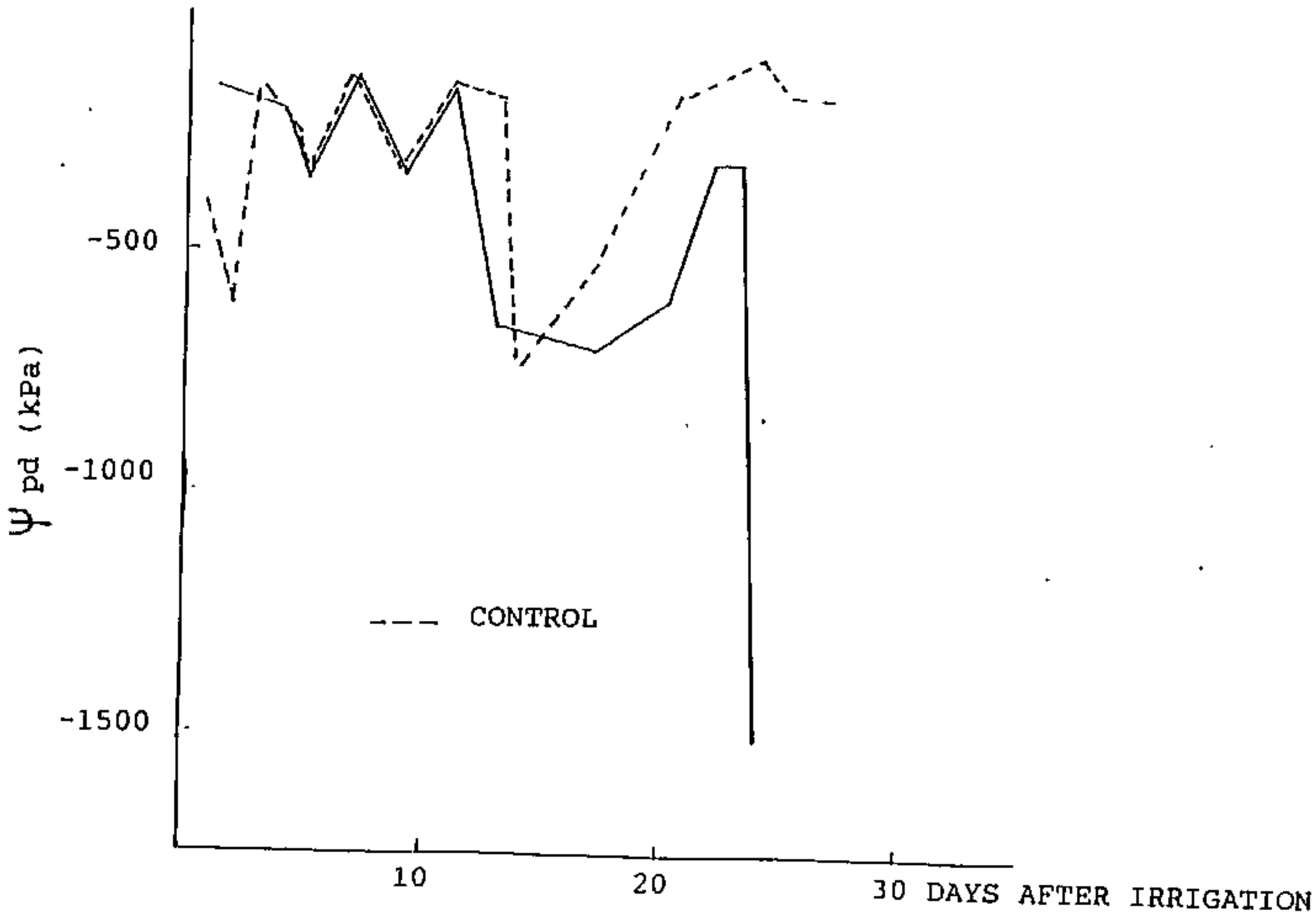
a 3.2



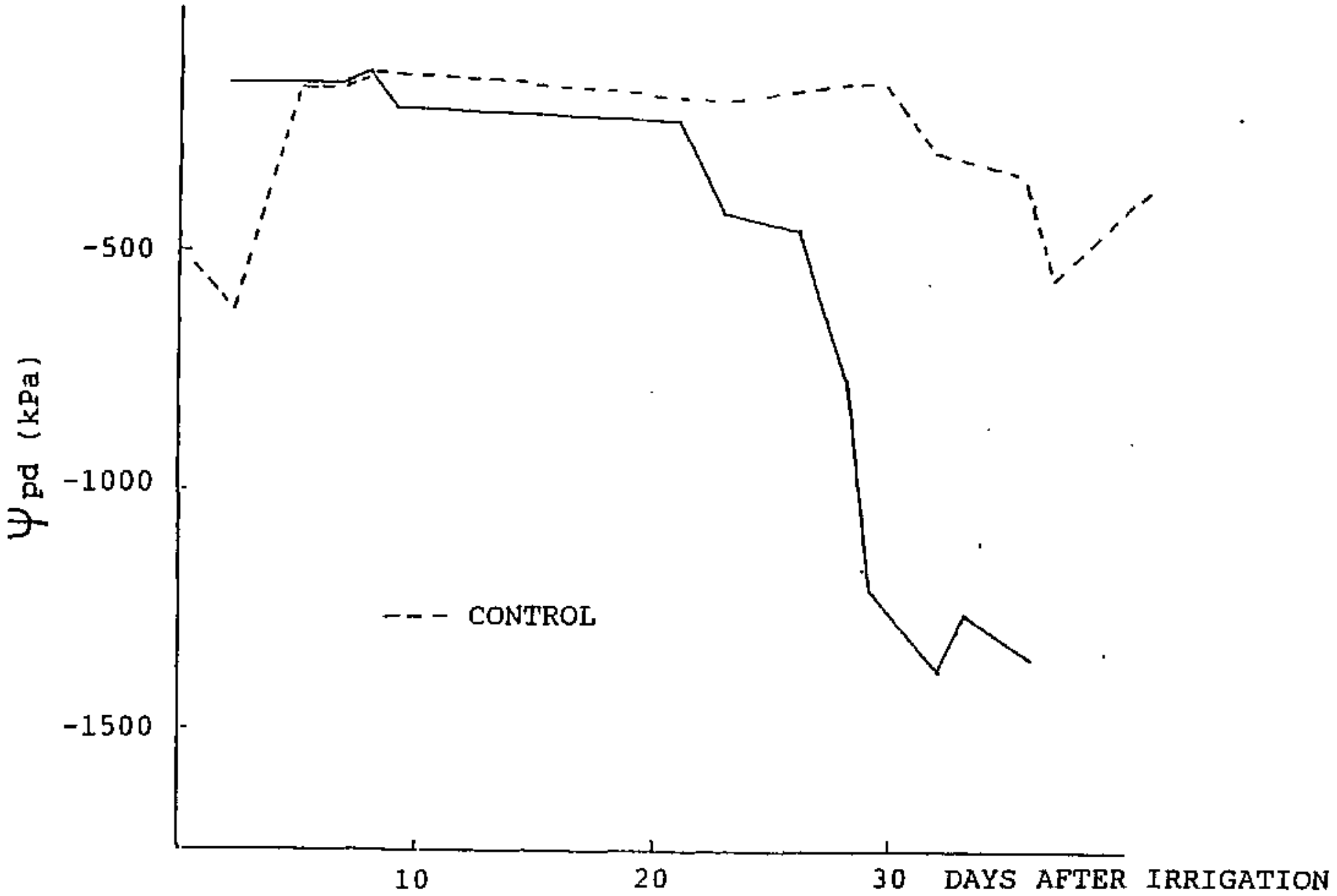
APPENDIX 3.2.13 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D16a (1987 SEASON)



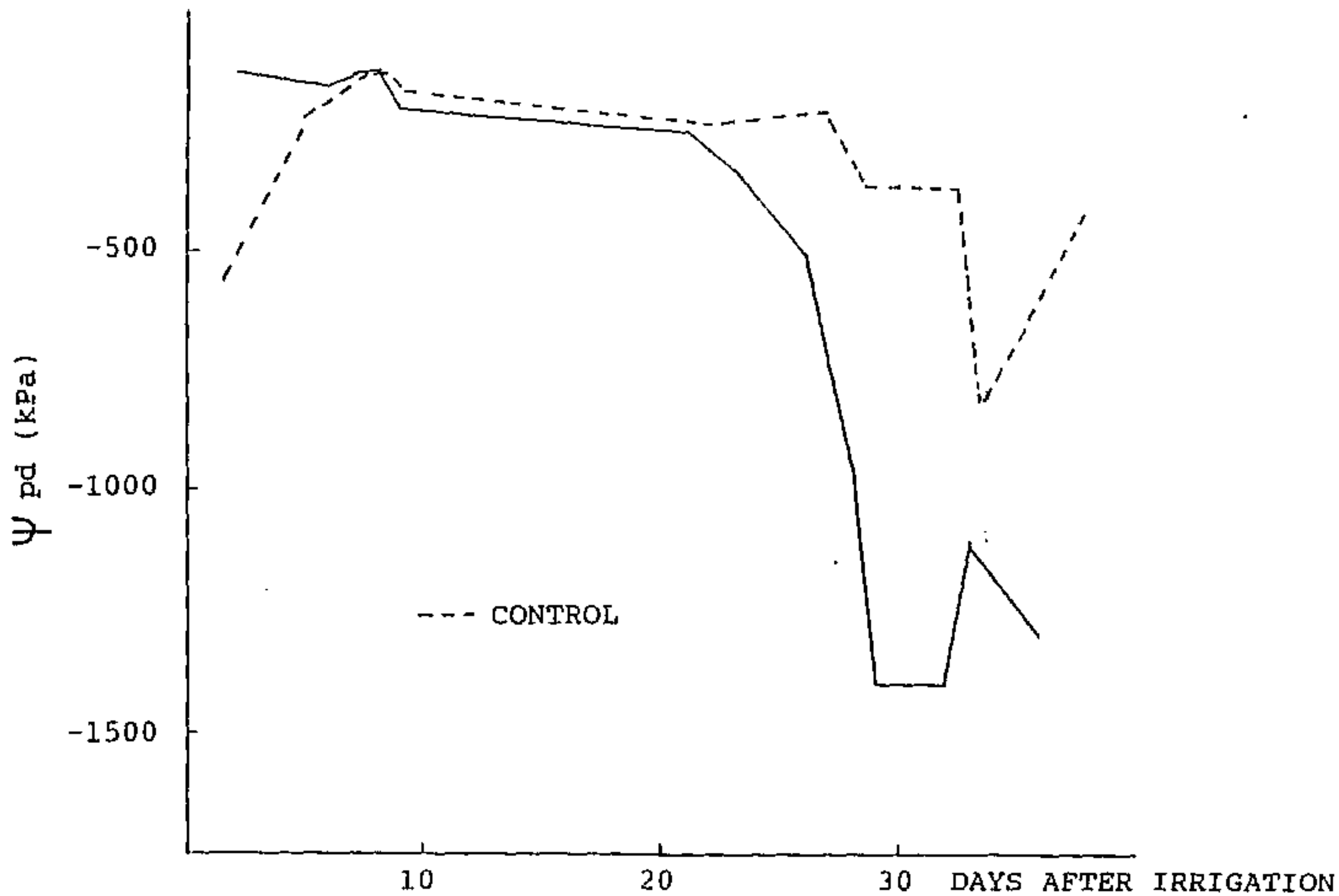
APPENDIX 3.2.14 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D12b
(1987 SEASON)



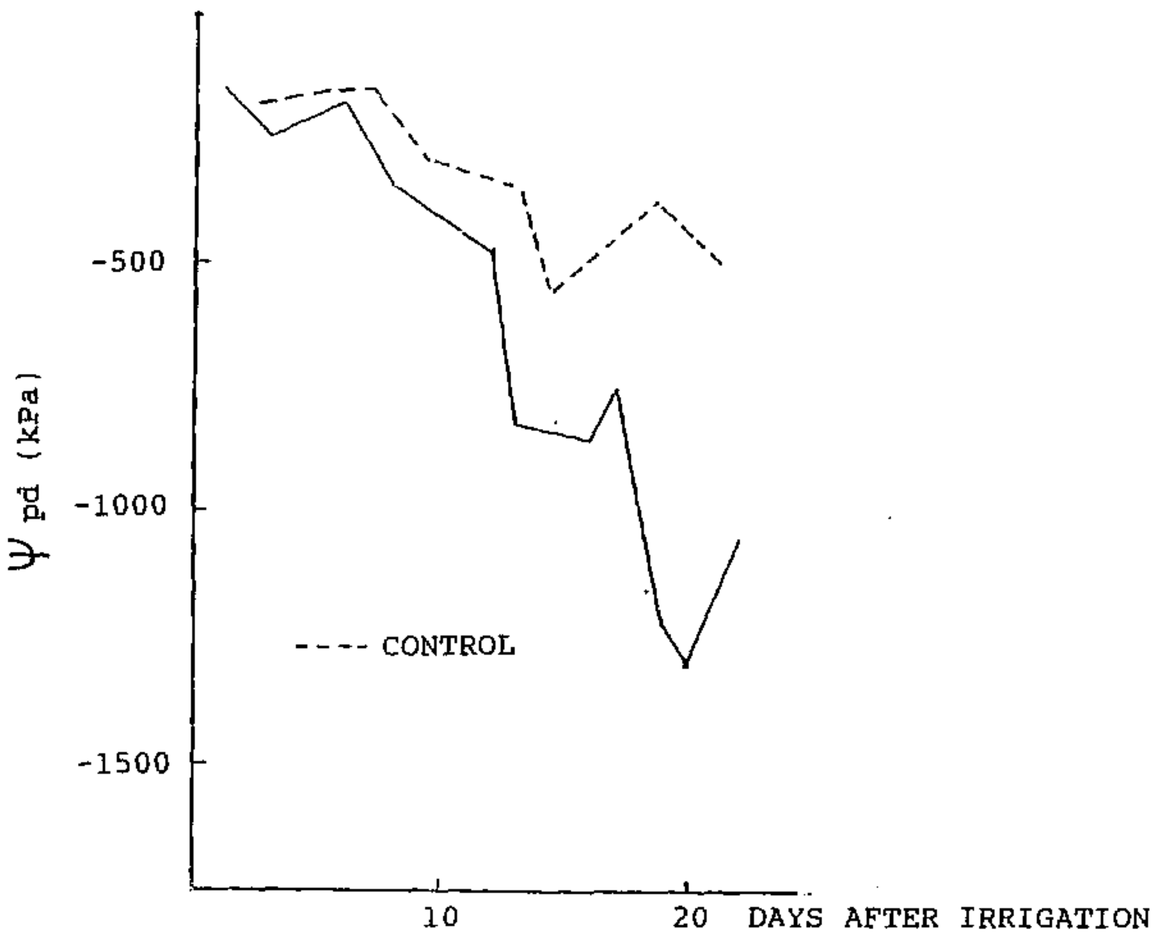
APPENDIX 3.2.15 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D16b (1987 SEASON)



APPENDIX 3.2.16 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D12c (1987 SEASON)

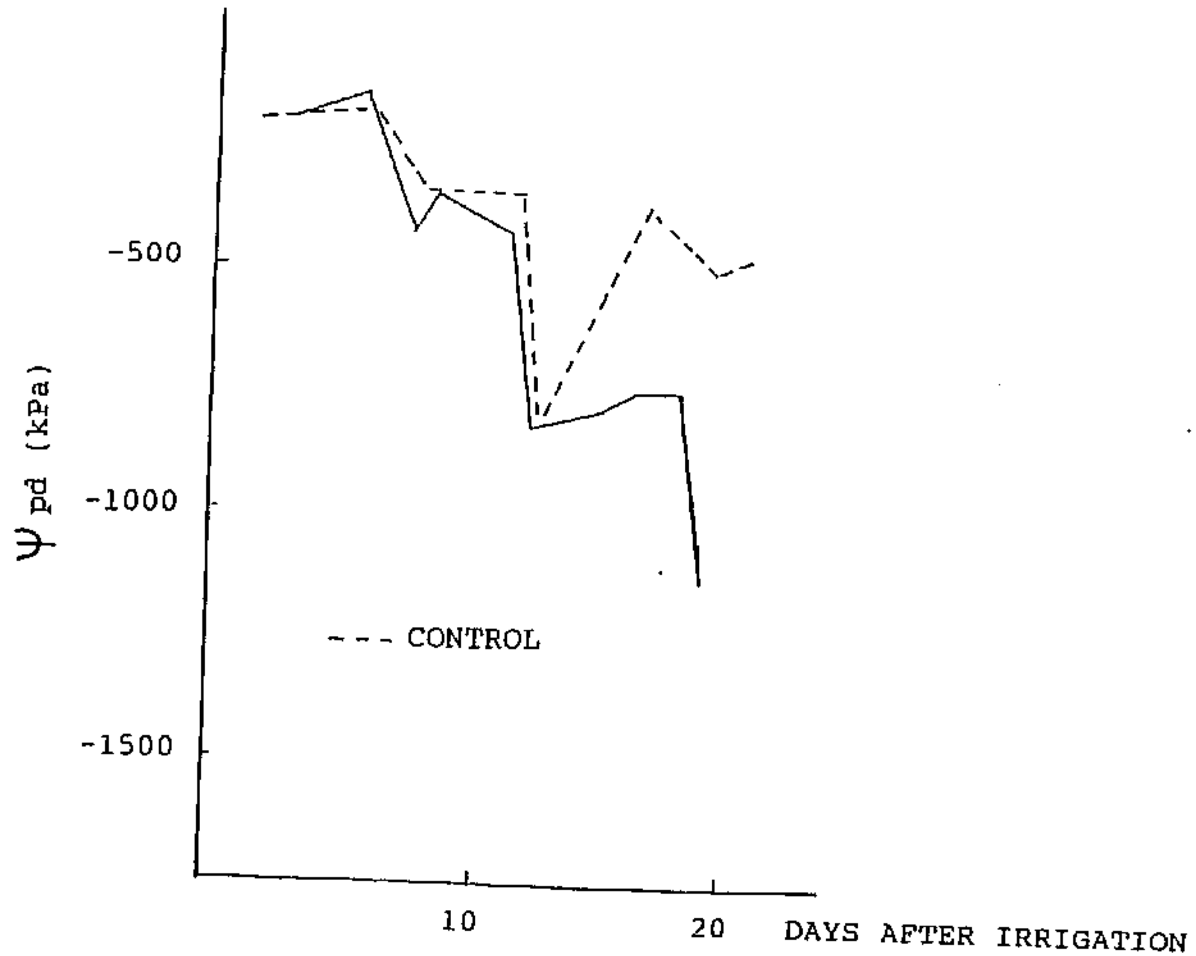


APPENDIX 3.2.17 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D16c (1987 SEASON)



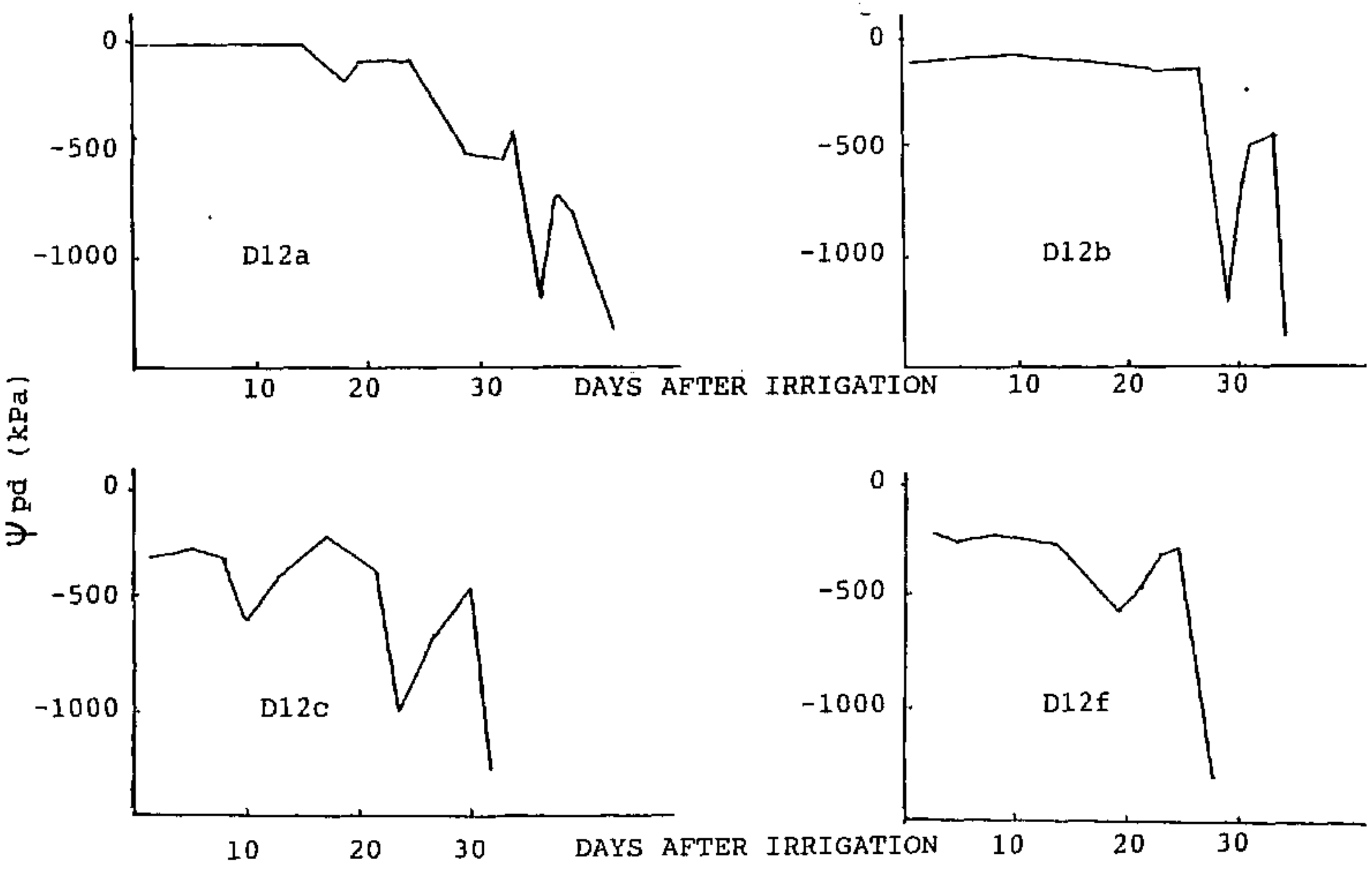
APPENDIX 3.2.18 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D12f (1987 SEASON)

a 3.2

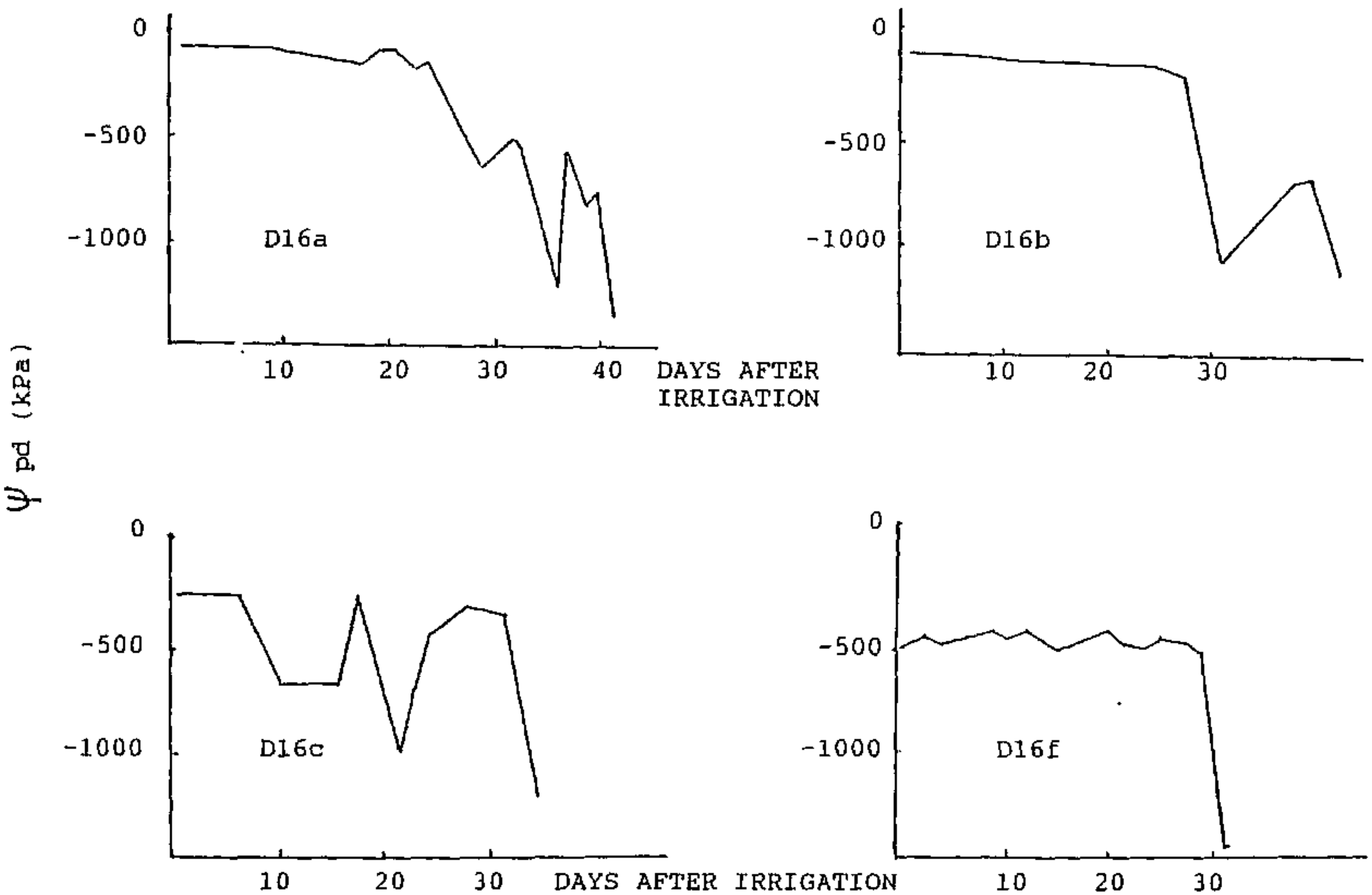


APPENDIX 3.2.19 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF DURUM WHEAT ON PLOT D16f (1987 SEASON)

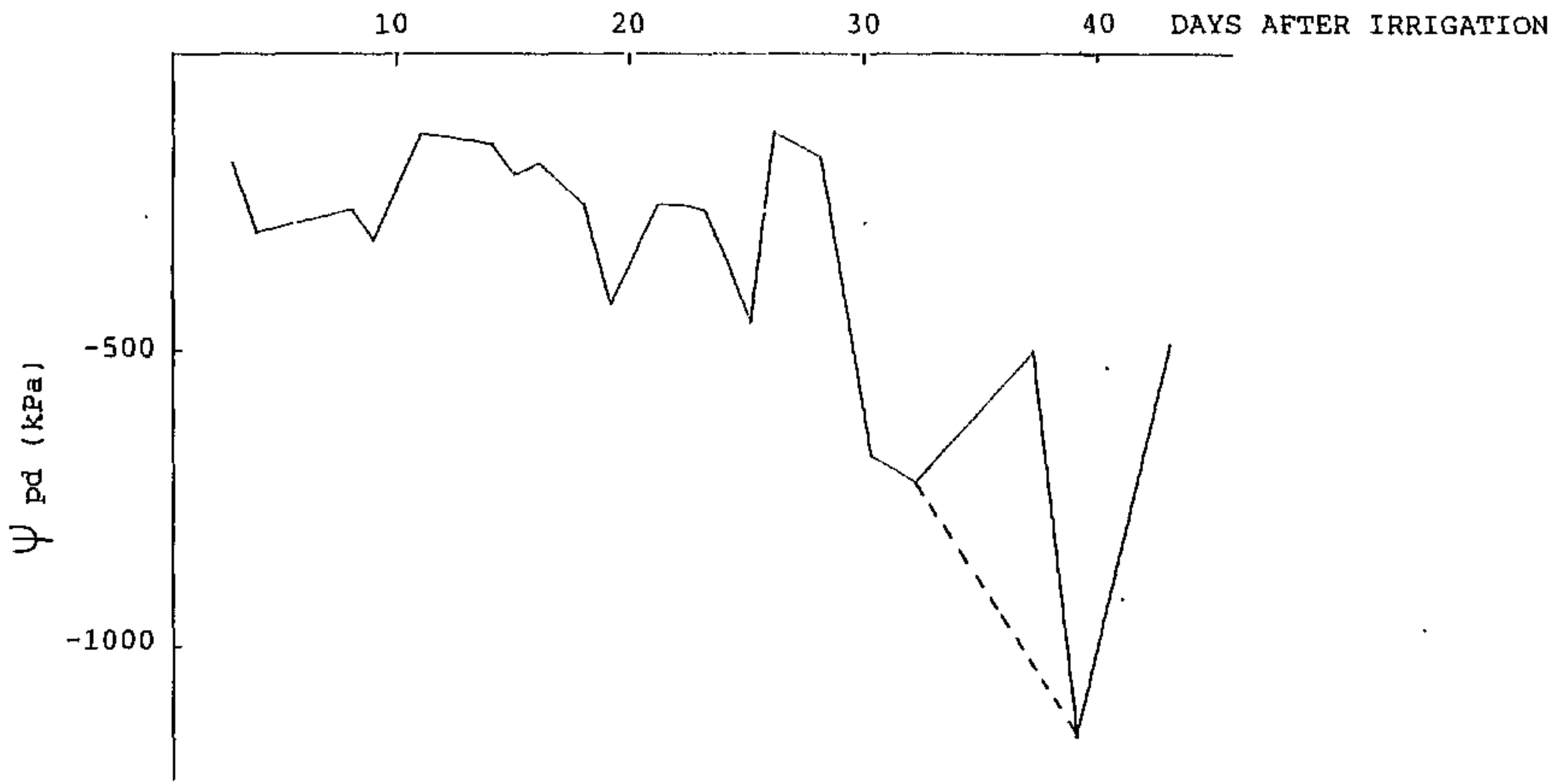
a 3.2



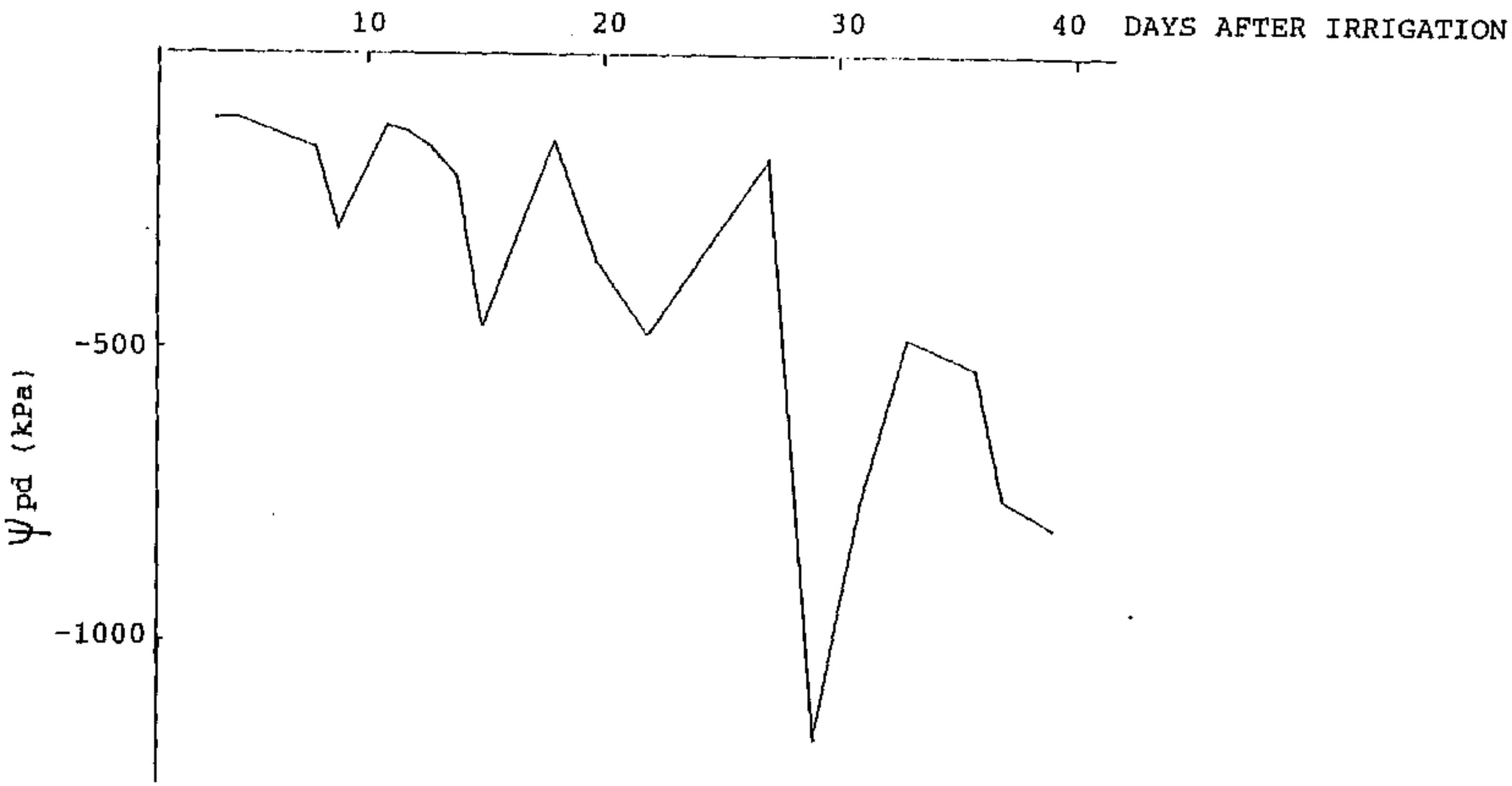
APPENDIX 3.2.20 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE AT SITE D12 (1985-1986 SEASON)



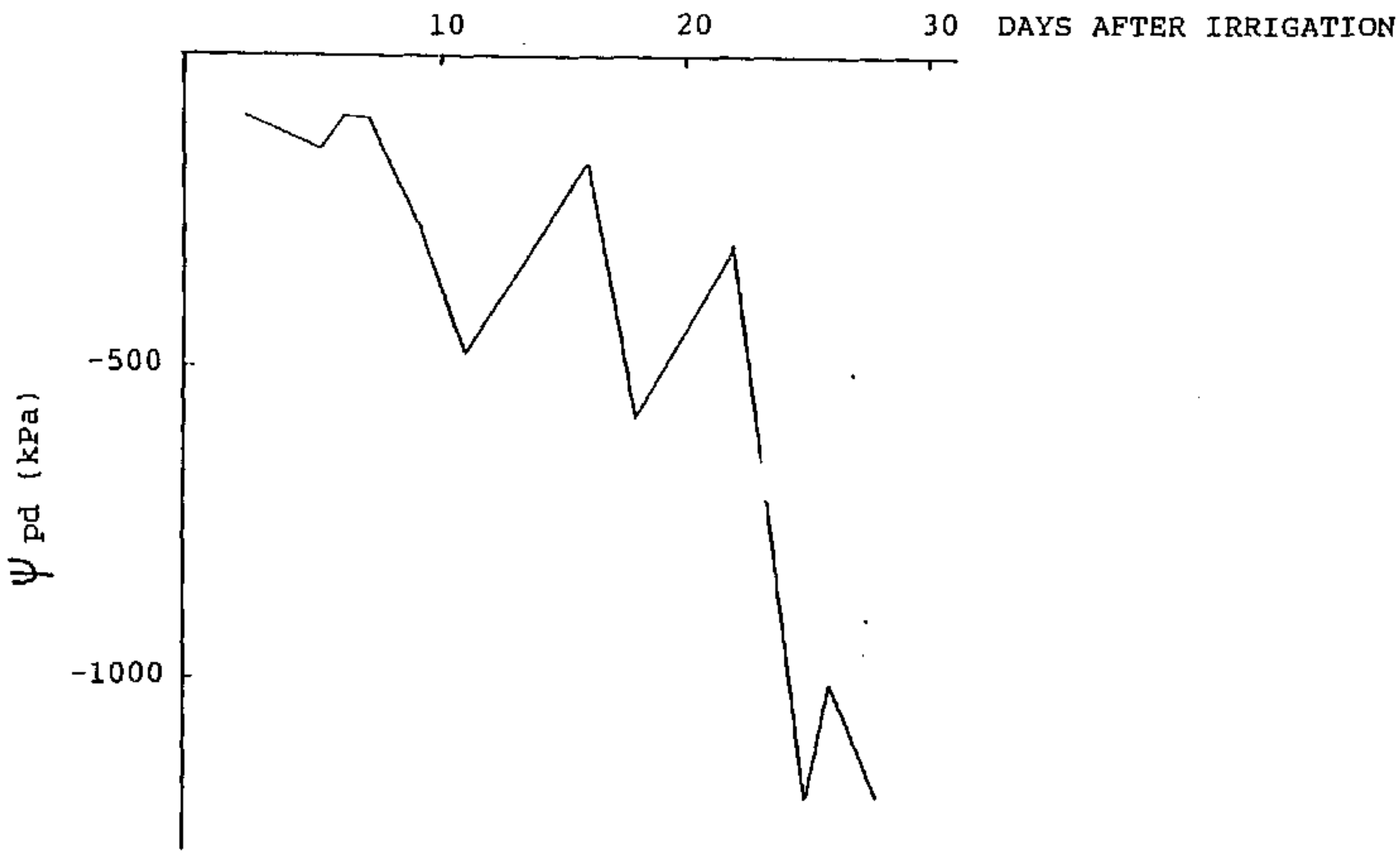
APPENDIX 3.2.21 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE AT SITE D16 (1985-1986 SEASON)



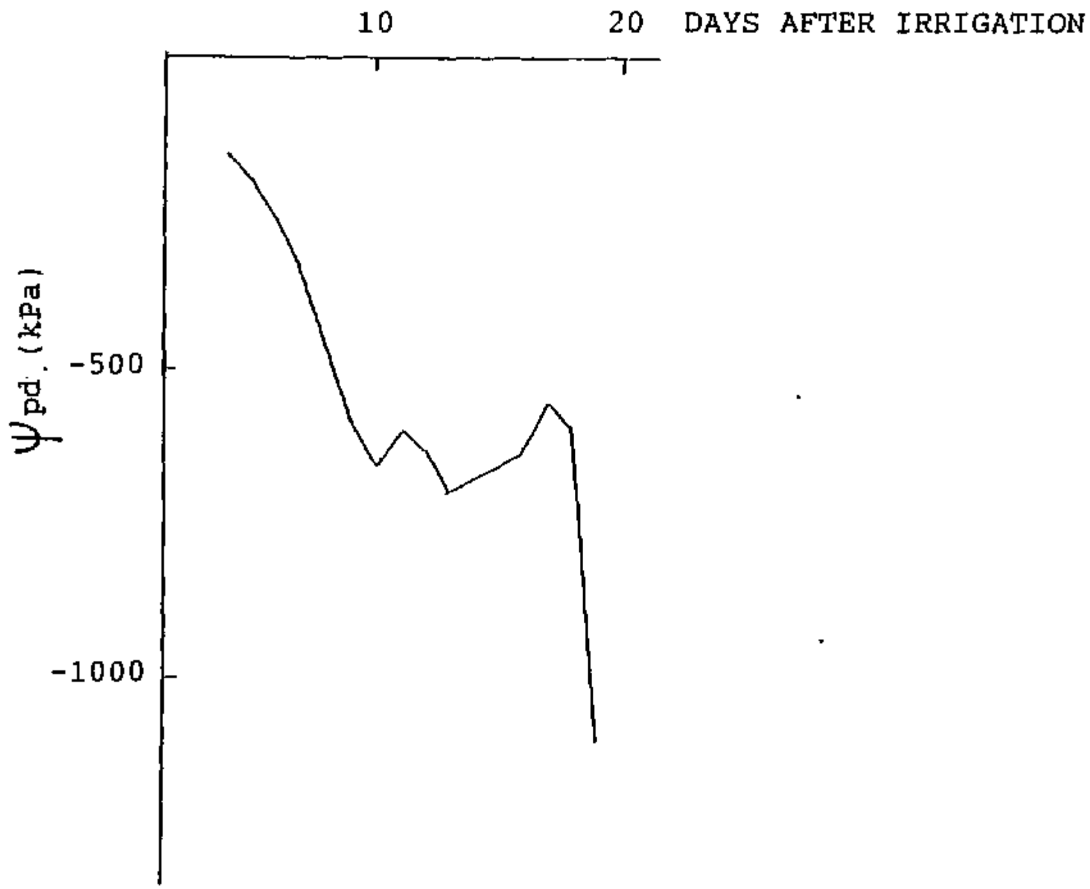
APPENDIX 3.2.22 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE ON PLOT D12a
(1986-1987 SEASON)



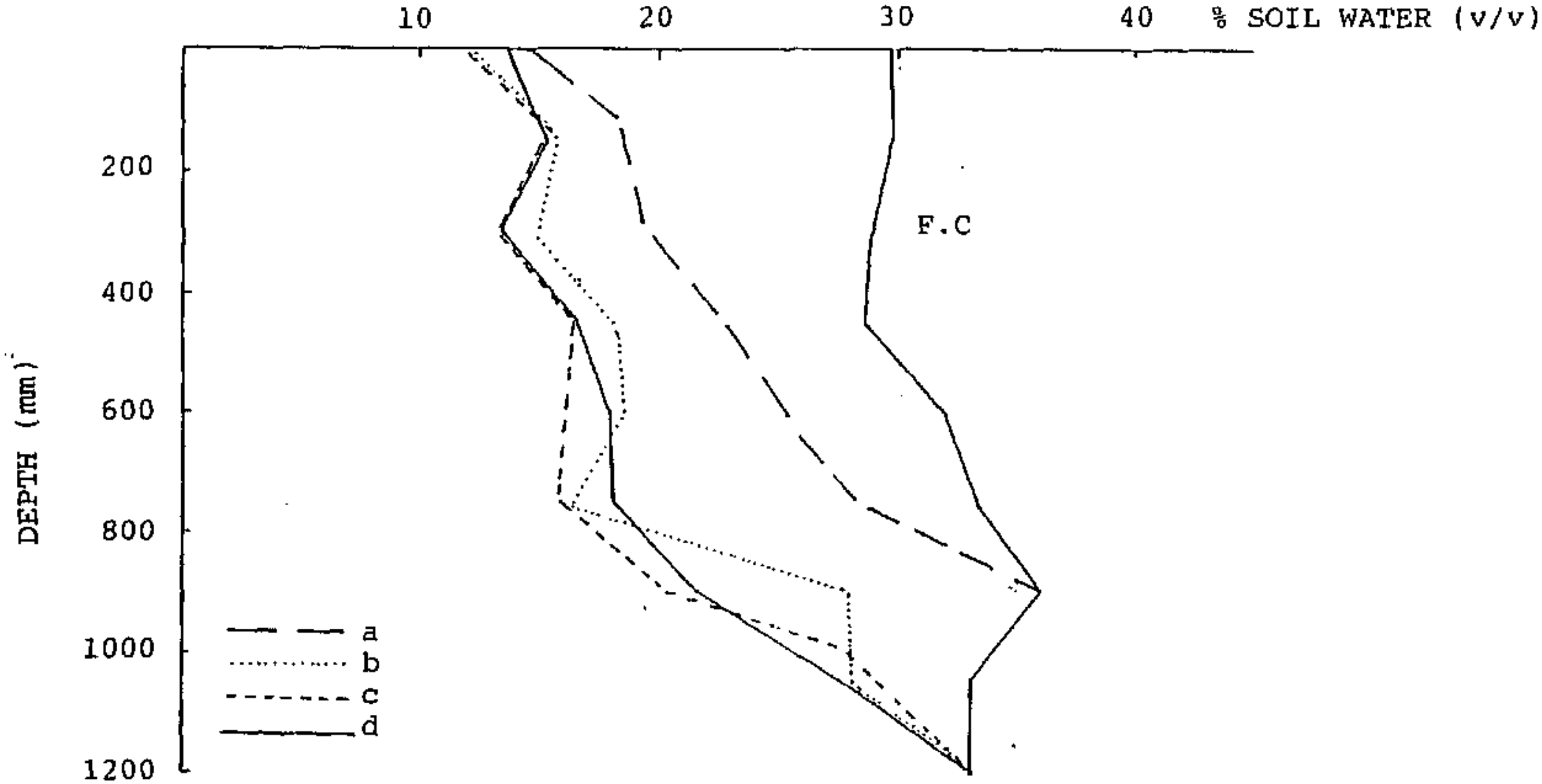
APPENDIX 3.2.23 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE ON PLOT D12b
(1986-1987 SEASON)



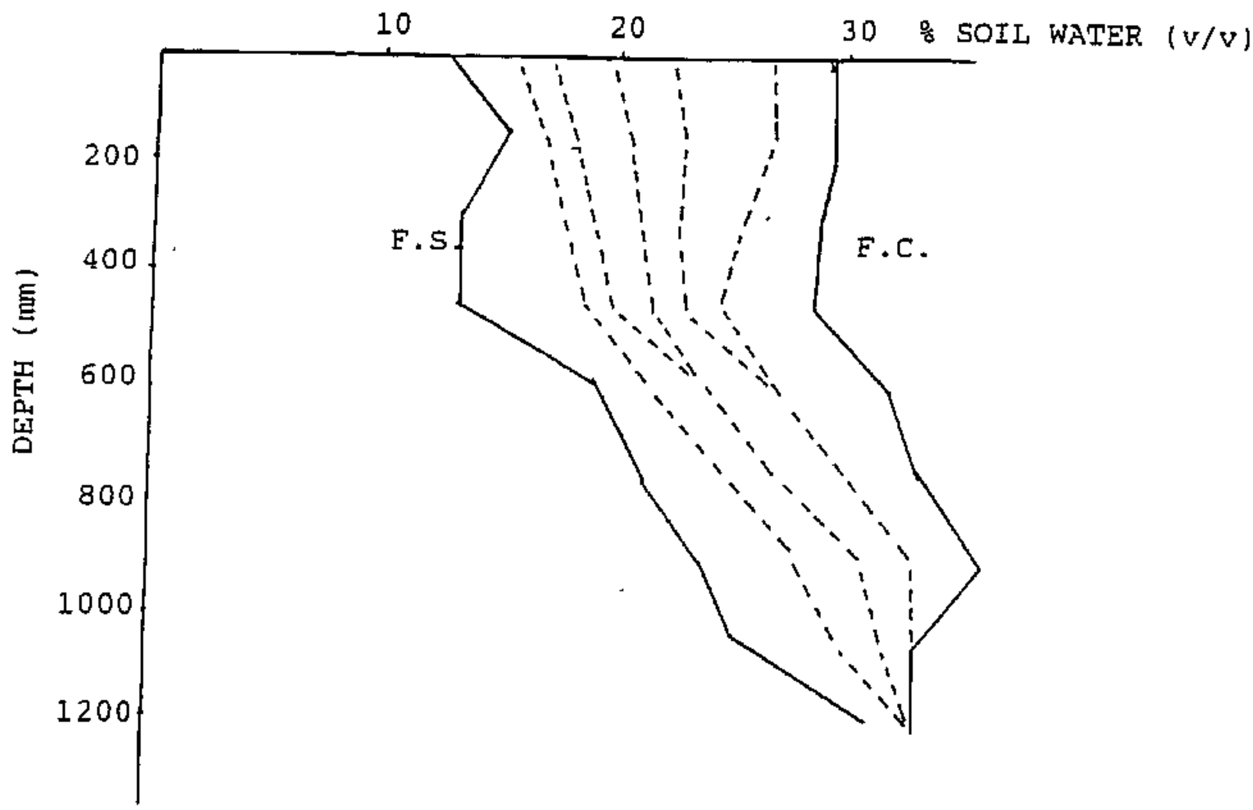
APPENDIX 3.2.24 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE ON PLOT D12c (1986-1987 SEASON)



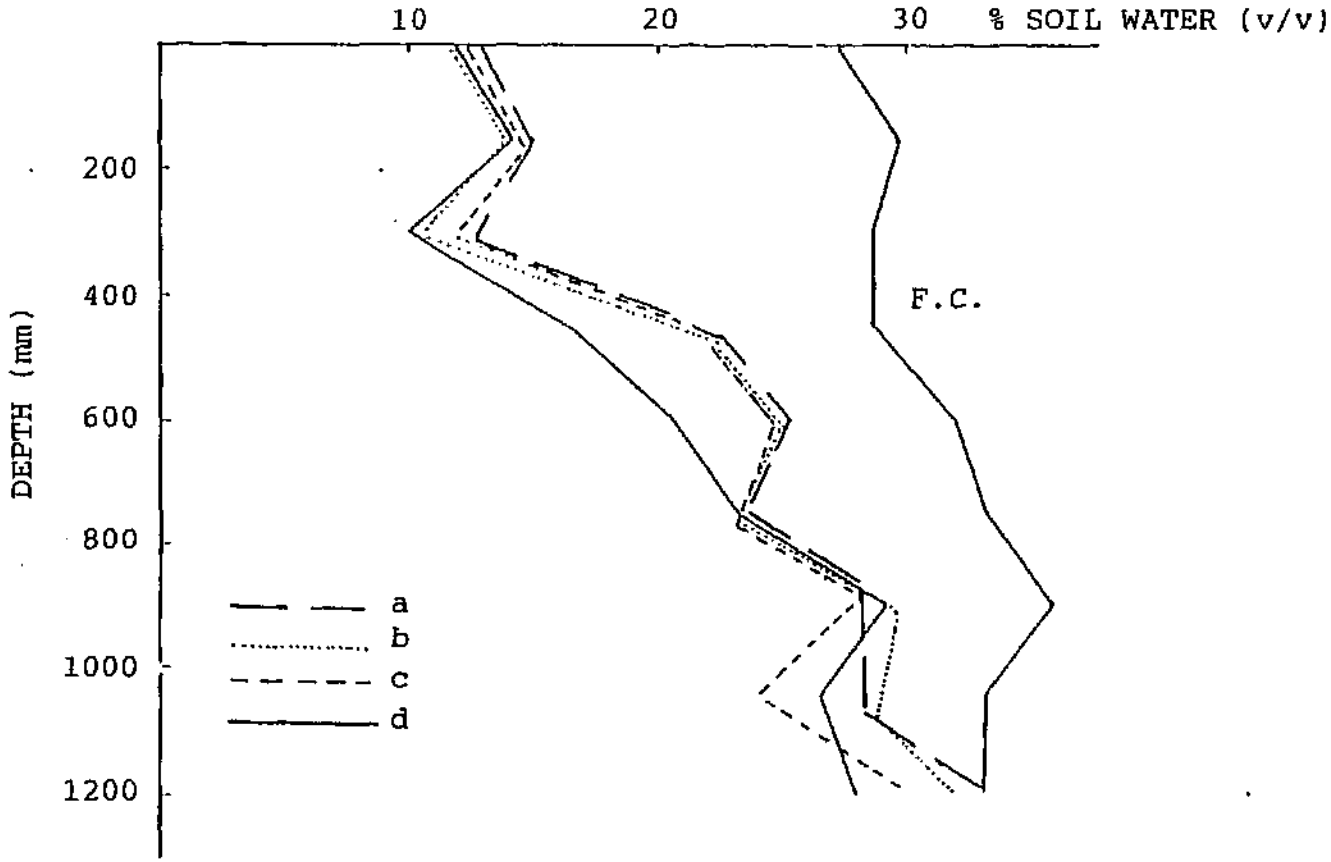
APPENDIX 3.2.25 PRE-DAWN LEAF WATER POTENTIAL PATTERN OF MAIZE ON PLOT D12d (1986-1987 SEASON)



APPENDIX 3.3.1 SOIL WATER EXTRACTION PATTERNS OF WHEAT AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D12 (1985 SEASON)

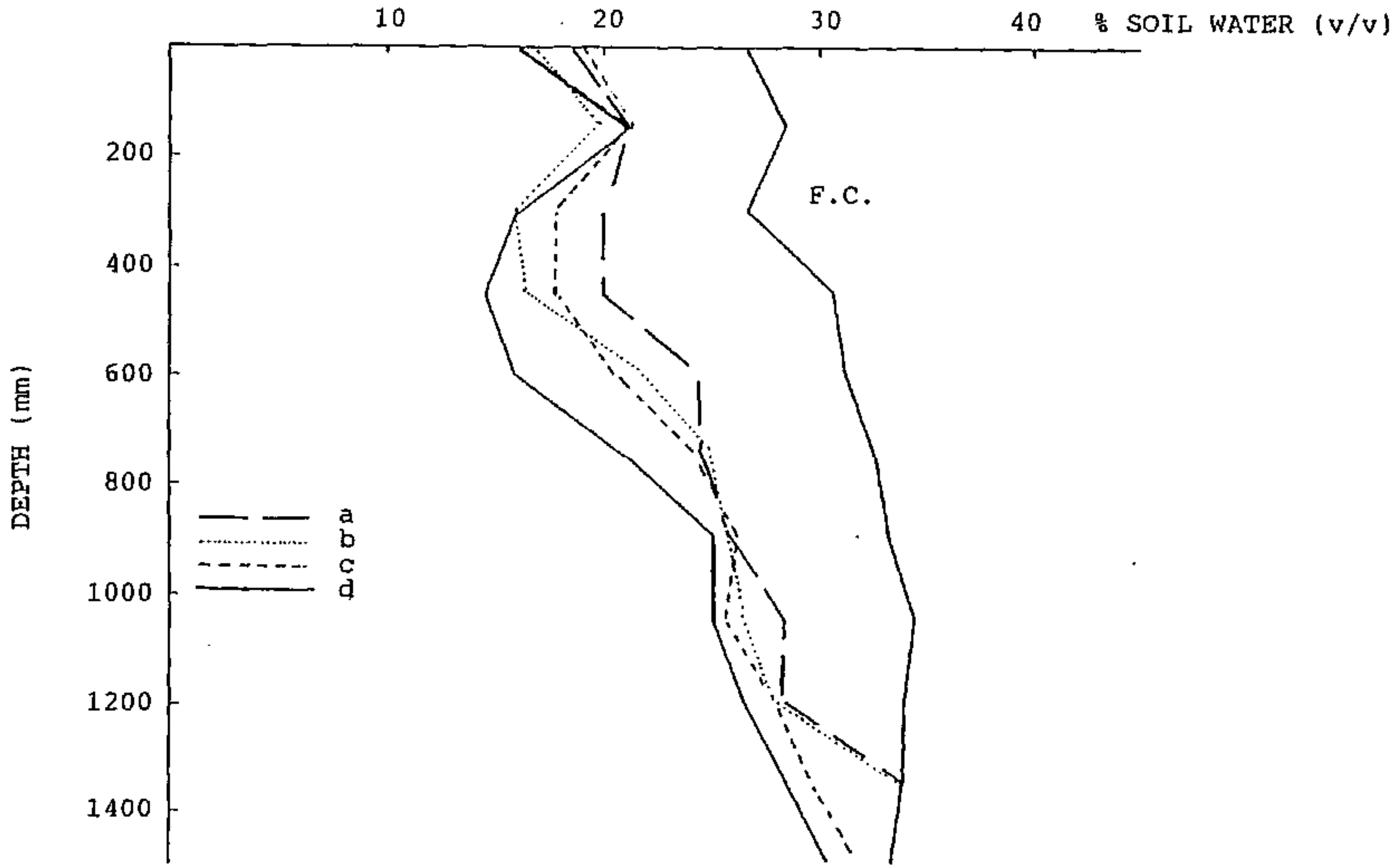


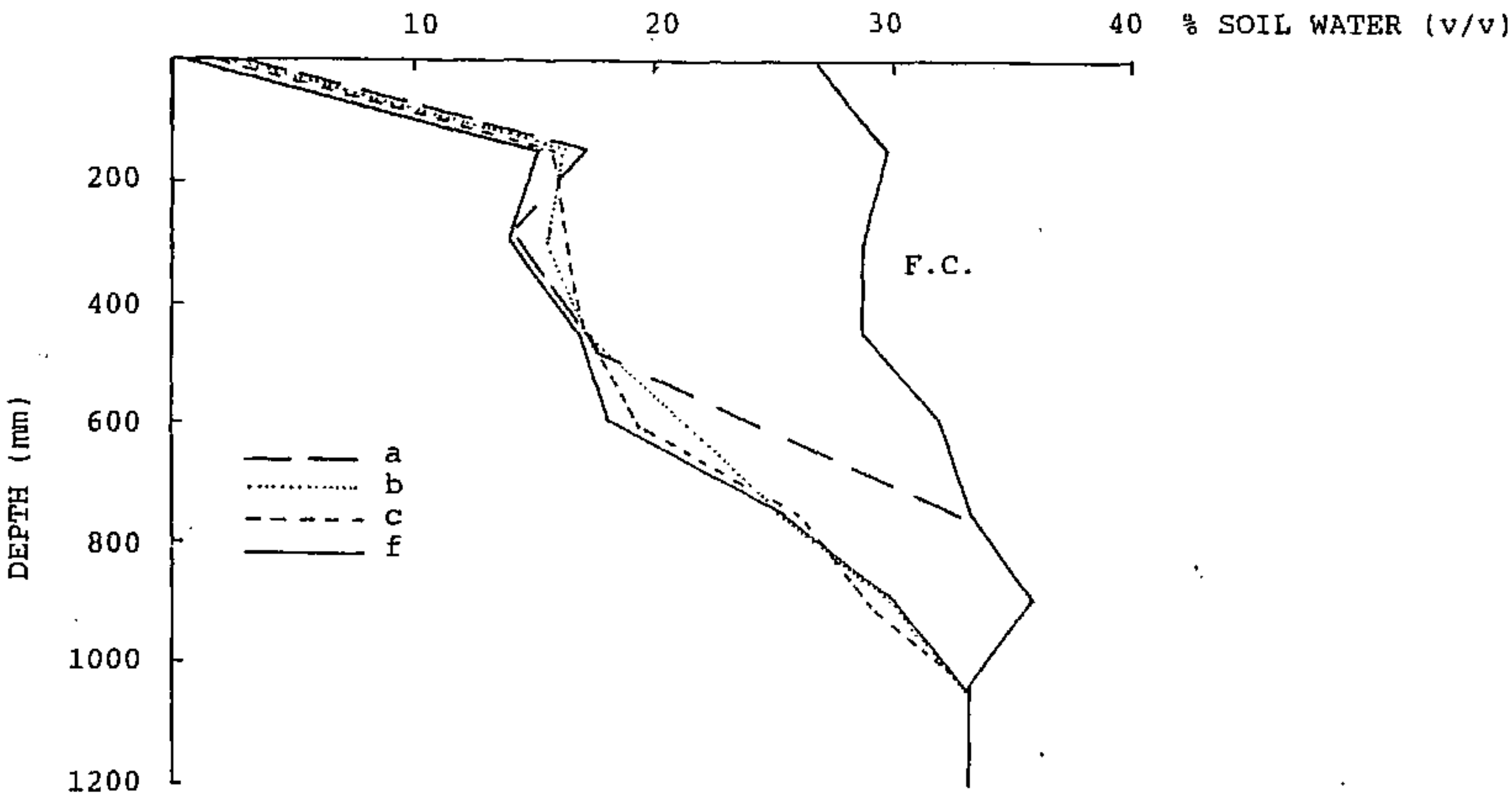
APPENDIX 3.3.2 EVOLUTION OF SOIL WATER EXTRACTION PATTERNS OF WHEAT AT FLOWERING STAGE UNTIL FIRST MATERIAL STRESS AT SITE D12 (1985 SEASON)



APPENDIX 3.3.3 SOIL WATER EXTRACTION PATTERNS OF WHEAT AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D12 (1986 SEASON)

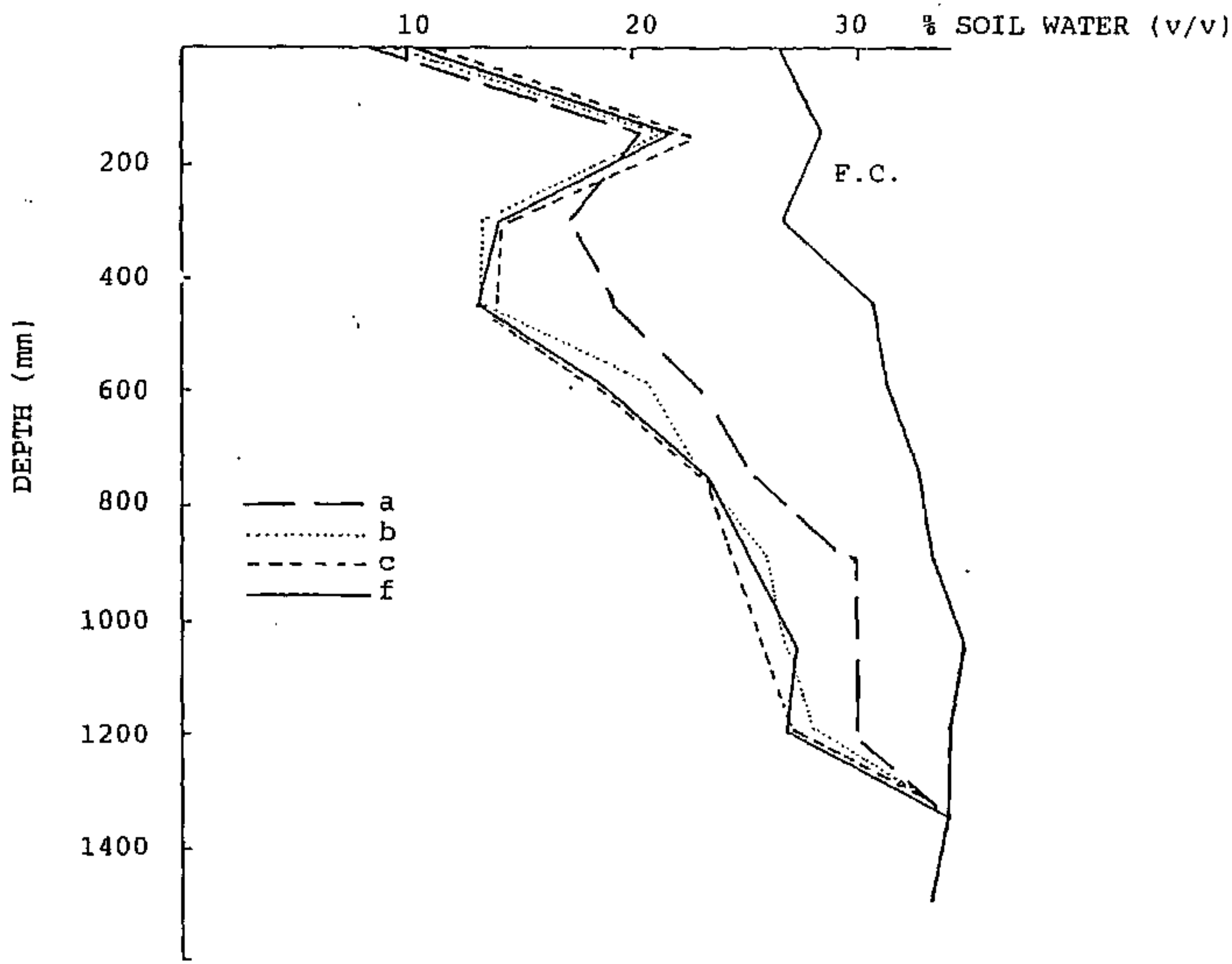
APPENDIX 3.3.4 SOIL WATER EXTRACTION PATTERNS OF WHEAT AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D16 (1986 SEASON)

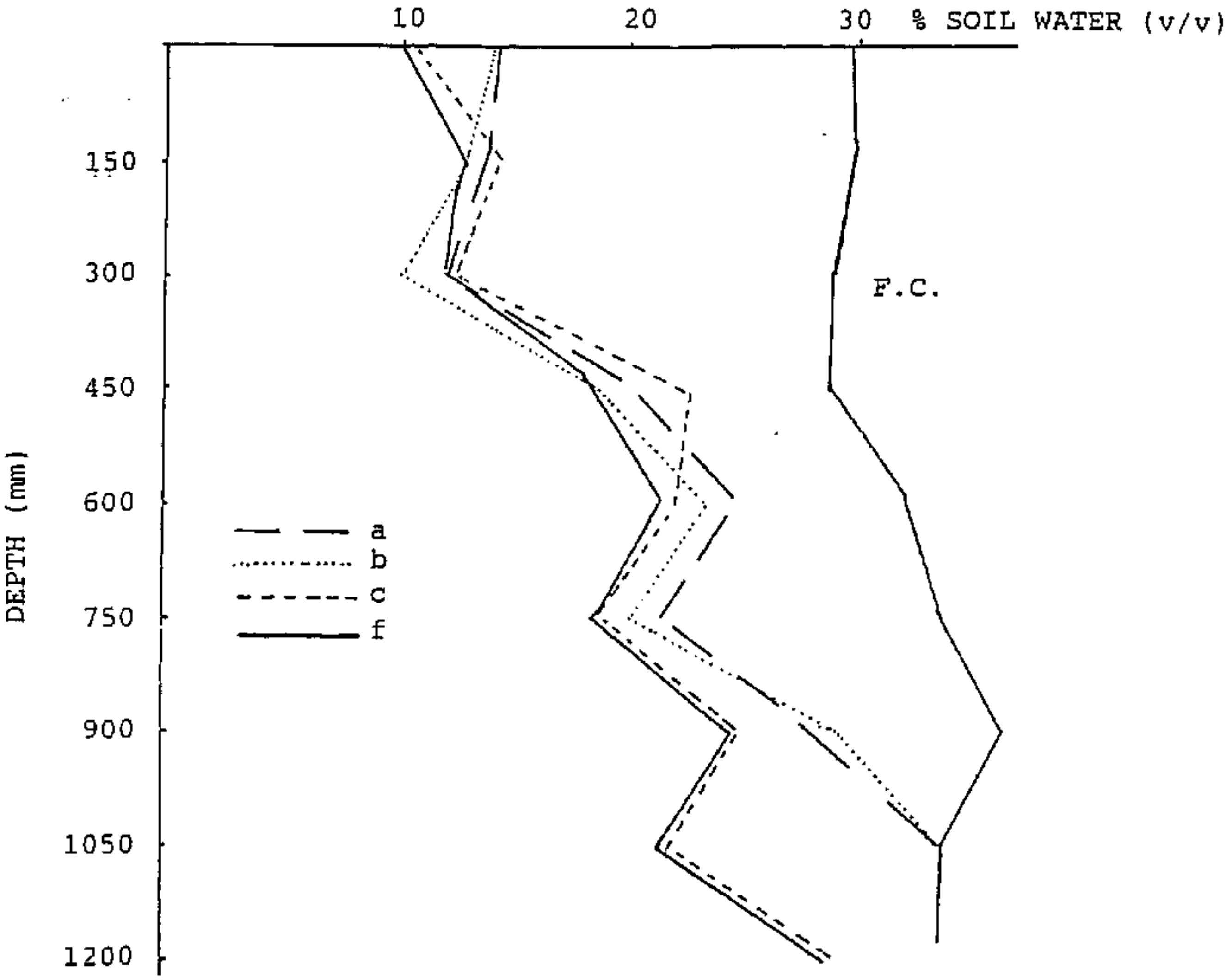




APPENDIX 3.3.5 SOIL WATER EXTRACTION PATTERNS OF DURUM WHEAT AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D12 (1987 SEASON)

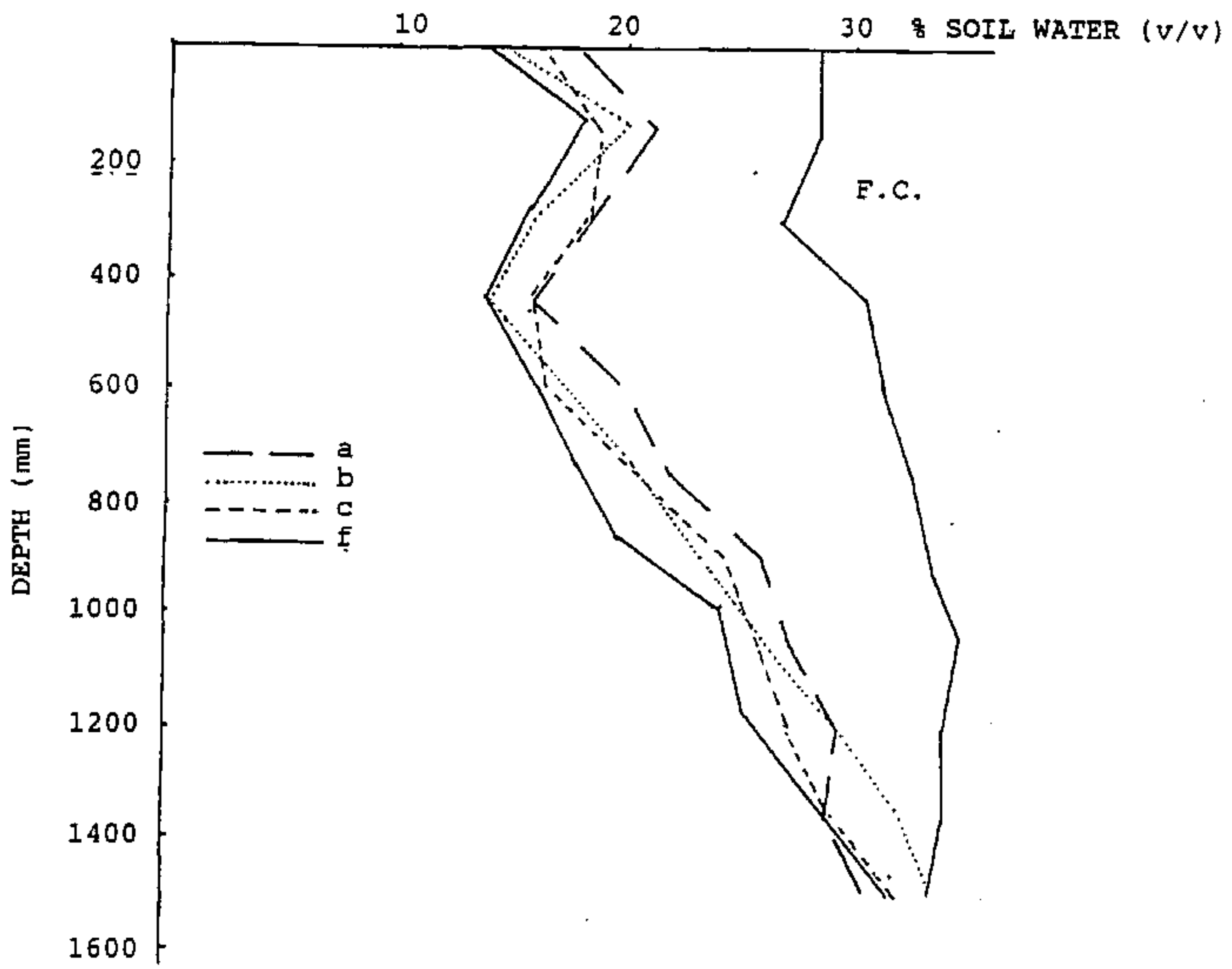
APPENDIX 3.3.6 SOIL WATER EXTRACTION PATTERNS OF DURUM WHEAT AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D16 (1987 SEASON)





APPENDIX 3.3.7 SOIL WATER EXTRACTION PATTERNS OF MAIZE AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D12 (1985-1986 SEASON)

APPENDIX 3.3.8 SOIL WATER EXTRACTION PATTERNS OF MAIZE AT DIFFERENT GROWTH STAGES AT FIRST MATERIAL STRESS AT SITE D16 (1985-1986 SEASON)



EFFECTS OF SOIL WATER STRESS ON STOMATAL DIFFUSION CONDUCTANCE AND LEAF WATER POTENTIAL IN MAIZE AT FLOWERING STAGE

M.C. Laker*, R.J.M. Ceulemans** and F.M.G. Vanassche***

* Department of Soil Science and Plant Nutrition, University of Pretoria, 0002 Pretoria, Republic of South Africa.

** Department of Biology, University of Antwerp, Universiteitsplein I, B-2610 Wilrÿk, Belgium.

***Department of Soil Science, University of Fort Hare, Private Bag X1314, Alice, Republic of Ciskei, South Africa.

* Address for correspondence

Running headline : Water stress effects on stomatal conductance.

MCL/sf

1987-08-04

ABSTRACT

Stomatal diffusion conductance, leaf temperature and xylem water potential of mature upper canopy leaves of maize (*Zea mays* L.), grown in a semi-arid region were measured at different times of the day under different irrigation treatments and soil water conditions at the flowering stage. Two different response patterns of stomatal conductance and xylem water potential to decreasing soil water content were observed. In a well-watered (unstressed) situation stomatal conductance and xylem water potential responded very sharply to atmospheric conditions, especially vapour saturation deficit and/or temperature. In the drier soil water range stomatal conductance responded very little to atmospheric conditions and decreased only slightly with decreasing soil water status. In this drier range xylem water potential decreased markedly with increasing soil water stress.

KEY WORDS: Maize - stomatal diffusion conductance - leaf water potential - profile available water capacity.

INTRODUCTION

In several parts of the world agricultural production is impossible without irrigation and therefore water use by agricultural crops should be as efficient as possible in those regions where water is a scarce resource. As an aid to understanding how the onset of plant water stress and water use responds to increasing soil water deficits in various climatic situations, it is necessary to know how different plant-water related parameters are affected. Predawn leaf water potential has been suggested as an appropriate diagnostic measurement of water stress with promise for irrigation scheduling, particularly for crops which require irrigation during a short but critical period (Dwyer and Stewart, 1984). Information on the use of predawn leaf water potential for this purpose has inter alia been obtained for maize plants in various parts of South Africa (Boedt and Laker, 1985). However, it has become apparent that satisfactory answers to the question when and how much to irrigate generally require a rather profound insight into the soil-plant-atmosphere continuum (SPAC; Jarvis, 1975; Milburn, 1979). The reason for this is that water loss from the soil to the atmosphere takes place mainly as a flow through the plant roots, stem and leaves. Whereas flow may be influenced in every segment of this pathway, the stomata are situated where the largest drop in water potential in the whole SPAC occurs and are, therefore, in the most advantageous position to control the flow of water from soil to atmosphere (Jarvis, 1975; Cowan, 1977; Jarvis and Morison, 1981). Moreover, stomata are the ports through which leaves exchange most of their gases with the environment. By opening or closing their pores, plants can regulate the loss of water (transpiration) and the uptake of carbon dioxide (photosynthesis; Milburn, 1979; Korner et al. 1979). Since transpiration represents latent heat exchange, stomata also indirectly affect the exchange of sensible heat between leaves and the air.

Numerous reports of in-phase changes in net photosynthesis and transpiration strongly implicate somatal control as a primary causal factor in decreasing net photosynthesis and water loss under water stress conditions, with stomata having a control function on plant transpiration (for review see Jarvis and Morison, 1981; Jones, 1973). Many studies on maize and other species have also shown that stomatal resistance constitutes a major fraction of the total (maize) leaf resistance to CO_2 assimilation. Strong evidence therefore exists for the stomata being the major limiting factor to photosynthesis (Miranda et al., 1981; Sanchez et al., 1983) and the prime controllers of photosynthesis by controlling the rates of CO_2 diffusion into the leaves (Vaclavik, 1980; Pearson et al., 1984).

For these reasons, as well as others, stomatal function under field conditions still needs to be more widely studied and understood. Factors which cause stomata to close are low light or darkness, high CO_2 concentration, and water stress (Allen et al., 1975; Jarvis, 1975; Jarvis and Morison, 1981).

This study was initiated to evaluate the effects of soil water stress situations on stomatal conductance and xylem water potential in maize plants at the critical flowering stage in a semi-arid climate (Karoo region in South Africa). This region experiences severe water deficiencies, especially during the summer season, and no crop production is possible without irrigation (Fig. 1).

MATERIALS AND METHODS

Maize (<u>Zea mays</u> L. cv. Pioneer PNR 542) was planted in November 1985 in five plots of 5 rows each at the Cradock Experimental Farm (Republic of South Africa; 32°08'S, 25°38'E; height above sea level : 660 m). Spacing was ca. 1 m between the rows and 20 cm within the rows, resulting in a plant density of ca. 50,000 plants. ha^{-1}. The soil of the experimental site was an Inceptisol of alluvial origin with a field capacity (FC) of approximately 475 mm and a profile available water capacity (PAWC) of 151 mm to a depth of 1.5 m. PAWC is defined here as the total volumetric amount of water between FC and first material stress (FS; Hensley and de Jager, 1982; Boedt and Laker, 1985; see also Fig. 2). Plots were irrigated at different time intervals, resulting in different soil water contents for the five plots. Plot E received the most frequent irrigation and plot B the least frequent. Soil water content was measured daily by means of a neutron hydroprobe (Campbell Pacific Nuclear, type CPN 503) every 0.15 m at ten different depths ranging from 0.15 m to 1.50 m. Maize plants were at the flowering stage at the time of measurements.

Measurements of stomatal diffusion conductance, leaf temperature, xylem water potential and incoming photosyn=thetically active radiation (PAR) were made three times daily, i.e. in the morning (08h00-09h00), at midday (12h00-13h00) and in the afternoon (15h00-17h00) on three consecutive days in mid-summer (January 21-23, 1986).

Stomatal diffusion conductance was measured in five replications on the abaxial side of mature, fully expanded upper canopy leaves with an automatic, ventilated diffusion porometer (a modified and improved Cayuga Developm., USA, porometer originally described by Carbonneau, 1983). Stomatal conductance readings were always taken in the middle of the leaf beside the midvein. Because significant distributional differences in stomatal conductance in different areas of the maize leaf blade may occur (Vaclavik, 1977) standardisation of the position of measurement is critically important.
The formula :

$$g_s = \frac{1}{r_2} * \frac{273}{R(273 + T_{leaf})} * \frac{10^4}{22.4}$$

where : T_{leaf} = leaf temperature (^oC)
g_s = stomatal conductance ($mmol.m^{-2}s^{-1}$)
r_s = stomatal resistance ($s.cm^{-1}$)

was used to convert measurements of stomatal resistance, made with the automatic ventilated porometer to conductance values, after Whale (1983).

Simultaneously with porometer measurements leaf temperature was measured with thin copper-constantan thermocouple (diam 0.51 mm; Omega Eng. Inc., USA) hair-clips clamped to the lower side of the leaves. Xylem pressure potential was measured at predawn and at different times during the day with a modified pressure chamber, described orginally by Scholander et al. (1965). Plant material was carried to the instrument in a sealed polythene bag covered at the inner side with aluminium foil to reduce errors due to loss of water subsequent to detachment from the plant.

At least four, randomly selected, mature leaves from different plants in each plot were used for xylem water potential determinations at any time. Readings were done on the veins, parallel to the main vein, of a piece situated in the centre of the leaf.

Immediately prior to the porometer and pressure chamber measurements, PAR incident on the sampled leaf was determined with a Lambda LI-190S quantum sensor (LiCor Inc., USA). The total (short- plus long-wave) net radiation balance of the maize vegetation was estimated at different times during the day with a properly calibrated Schenk net radiometer (Ph. Schenk, Austria) just above the canopy. Dry bulb temperature and air vapour saturation deficity (VSD) were monitored continuously with a calibrated thermohygro= graph on the nearby meteorological station of the Cradock Experimental Farm. Some meteorological and environmental conditions on the days of measurements are given in Table 1.

RESULTS

The trend with time of the amount of soil water during the measuring period is shown in Fig. 2. Values were calculated from the neutron hydroprobe readings and specific calibration data for the soil profile according to the method used by Boedt and Laker (1985). The water content of the soil profile was depleted steadily during the measuring period. Plots A and B were water stressed plots; plots D and E were well watered, unstressed plots receiving frequent irrigation. Plot C was intermediate. In terms of PAWC 100, 110, 75, 40 and 45% of PAWC were extracted from Plots

A, B, C, D and E respectively by January 23, 1986. A typical example of soil water profiles with depth, representing these extractions, is given in Fig. 3. Mean water extraction patterns for stressed plots (A and B) and unstressed plots (D and E) respectively on January 23, 1986 are represented on this figure. Maize roots extracted soil water effectively to a depth of 1.5 m in these Inceptisols. For reference purposes the soil water profiles at field capacity and first material stress, the upper and lower limits of PAWC, are also given. First material stress is defined as the volumetric profile soil water content at the point of water depletion beyond which further soil water depletion will cause significant decreases in plant physiological processes or yield. Treatments were not materially affected by the small quantity (3 mm) of rain recorded on January 21, 1986.

Diurnal changes in atmospheric and leaf temperatures, air VSD, incoming PAR and net radiation balance of the maize canopy are presented in Figure 4. The cloudy, cool, humid conditions associated with the light rain shower on January 21, 1986 modified the patterns for that day.

On any particular day stomatal conductance of unstressed plants responded in a cl: ical way to increasing PAR (Figure 5) and a rectangular hyperbola could be used to describe the conductance-PAR response curve (Whale, 1983). All points in Figure 5 are mean values of five replications on different leaves in the unstressed plots. One could, however, expect partial stomatal closure in plants of the drier or stressed treatments at high PAR levels. This is supported by the finding that in contrast to the early morning situation regarding stomatal conductance, which was environmentally controlled and independent of soil water status over the whole PAWC range (and even somewhat beyond it), the further run of g_s to midday is a function of both soil water status and environmental factors (Figure 6). The pattern for unstressed plots is totally different from that for stressed plots.

In the case of unstressed plants there was an almost consistent increase in g_s from early morning until midday on the different days, as shown by the virtually parallel lines on Figure 6a. Midday stomatal conductance values differed markedly between the different days. This is apparently associated with early morning environmental differences, which set a certain pattern, rather than midday environmental conditions. It appears that in this moist water range soil water conductance was adequate to cope even with the highest g_s demands under the conditions prevailing on these three days. In this way scenario A of Figure 7 is caused, viz. sharp daily fluctuations in midday stomatal conductance - in response to differences in early morning environmental conditions (especially temperature and VSD).

In the case of stressed plots (Figure 6b) there was a very slight increase in stomatal conductance from early morning to midday on the day with a low early morning conductance. Stomatal conductance remained constant until midday on the day with an intermediate early morning value and dropped sharply on the day with a high early morning value. At this low soil water status soil water conductance is clearly a limiting factor, causing the failure of the system to maintain a high stomatal conductance after a high early morning start. A further consequence is that the daily variations in midday stomatal conductance in this dry soil water range are very small (scenario B of Figure 7).

Unfortunately no very high early morning stomatal conductance values, such as the values of 700 to 800 $mmol.m^{-2}\ s^{-1}$ by 08h00 found by Ceulemans et al (1987), occurred during the period of this study and consequently situations where well-watered systems failed to cope were not observed in the present study.

Late afternoon (16h00 to 17h00) stomatal conductance values were, as in the case of the early morning values, independent of soil water status, but for each plot (and the average) closely related to VSD at the time of measurement (Figure 8). Early morning g_s was in fact more closely related to air temperature than to VSD. This was not the case with late afternoon values.

Early morning (08h00) xylem water potentials were constant at about -1.0 MPa, irrespective of soil water status or environmental conditions on the three days of the measurements (Figure 9). The value of -1.0 MPa is probably lower than one would expect for the well-watered plots, but higher than would have been expected for stressed plants. The latter is probably a confirmation of the g_s data which gave an indication that the plants of the "stressed" plots were not under severe stress (in the sense that they were still able to maintain a reasonable level of stomatal conductance). Between early morning and midday the logically expected sharp decrease in xylem leaf water potential occurred. As in the case of stomatal conductance the midday patterns for stressed and unstressed plots differed markedly for xylem water potentials. In the case of stressed plants the midday values were almost constant at about -1.8 MPa for all three days (Figure 9a). In the unstressed plants there was a sharp daily variation in midday $_x$, similar to the pattern found for g_s (Figure 9b). Midday xylem water potential was inversely related to early morning VSD and stomatal conductance. In other words, it decreased more, the higher the water demand was. On the day with the highest early morning VSD and morning and midday stomatal conductance $_x$ decreased to -1.8 MPa, the same value as for the stressed plots. During the late afternoons xylem water potential recovered somewhat, in response to the decreases in VSD and stomatal conductance during these periods. As could be expected, this recovery was less for the stressed than for the unstressed plots except on the day with the cloudy afternoon (Jan. 21). On the latter day they reached identical values.

DISCUSSION

It is well established that plants are able to respond to the VSD gradient between leaf and ambient air by stomatal control of transpiration (Jarvis and Morison, 1981). In the study reported here there was a strong positive response of midday stomatal conductance to increasing early morning VSD gradients at relatively high levels of available soil water. At low levels of available water the response was variable. Other factors, such as soil-root resistances, most probably became overriding under the latter conditions.

The diurnal patterns of stomatal conductance indicate major stomatal opening during early morning on all plots. On well-watered plots stomatal conductance increased from then on to peak around midday, after which it decreased again. On relatively dry plots stomatal conductance was high during early morning on the day with high early morning VSD, but then declined sharply towards midday. This indicates an inability of the soil-plant system to cope with water demand under these conditions. More detailed diurnal patterns for maize under more extreme conditions, causing such declines in stomatal conductance from mid-morning to midday even on well-watered plots are reported by Ceulemans et al. (1987). The observed diurnal patterns agree more or less with those reported for maize by Catsky et al. (1973). The values of stomatal conductances are in the same order of magnitude as those reported for maize by Catsky et al. (1973), Korner et al. (1979) and Pearson et al (1984). The reduction in stomatal conductance in stressed plants under conditions of high demand indicates the response of maize plants to drought stress, confirming the findings of other researchers for maize (Catsky et al. 1973; Dwyer and Stewart, 1984; Ogata et al. 1985).

No distinct PAR saturation was observed below 1.8 mmol. m^{-2} s^{-1}, which is in the same range as the results of Catsky et al. (1973) and Vaclavik (1980) for maize. It is, however, rather high compared to results reported by JARVIS (1975) for various other species and by Allen et al. (1975) for peanuts.

Where soil water availability is restricted, the feed-forward nature of the stomatal response (Jones and Muthuri, 1984) clearly has the effect of conserving soil water supplies and maximizing daily photosynthesis for a given level of transpiration, in line with the model of optimal stomatal function proposed by Cowan (1977). This feed-forward stomatal control might also be reflected in the response of stomatal conductance to soil water stress on Fig. 6 and might partially explain (together with the increased soil-root resistance) why g_s remained low on the relatively dry plots on the days that it shoots up on the well watered plots. Studying responses of transpiration and diffusion resistances to soil moisture stress in four Plantago species, Sawada and Sugai (1984) also reported considerable increases in stomatal resistance, supporting a nearly constant water use efficiency as the soil water content decreased. Responses of stomatal conductance to drought stress similar to Scenario B (Fig. 7) have been reported a.o. for Plantago species by Sawada and Sugai (1984), for soybeans by Zur and Jones (1984) and for maize by Ogata et al. (1985). The reduction of stomatal conductance of maize leaves with water stress could be further accentuated by potassium application (Khanna-Chopra et al., 1980).

According to Khanna-Chopra et al. (1980) and Dwyer and Stewart (1984) the threshold level of xylem water potential for induction of stomatal closure and significant restriction of transpiration and photosynthesis in maize is aroung -1.5 MPa, but Alvino and Zerbi (1980) claimed that maize had no threshold leaf water potential corresponding to a rapid decrease of stomatal conductance. The results reported here for field conditions apparently support the latter. However, under specific and controlled conditions a significant correlation between maize leaf water potential and stomatal conductance affected by drought stress might be observed (Jordan et al. 1975; Ackerson, 1980; Ogata et al. 1985).

Significant stomatal closure under drought stress conditions prevented deleterious loss of transpirational water. In this manner, maize plants protected themselves against drought stress by drastically closing their stomata after most of the so-called available soil water has been extracted.

ACKNOWLEDGEMENTS

This joint study forms part of a four year research project financed by the South African Water Research Commission. The authors are very grateful to A.G. Bezuidenhout, P. van Heerden and the staff of the Cradock Experimental Farm for their assistance, to F. Kockelbergh for excellent technical assistance and indispensable assistance with gathering field data, and to E. Smith for assistance in the field and for computer calculations. Dr. G.C. Green (Water Research Commission, Pretoria) and Dr M. Lindhauer (Kali und Salz, Hannover) are thanked for their critical and constructive comments on an earlier version of the manuscript.

LITERATURE

ACKERSON, R.C., 1980 - Stomatal response of cotton to water stress and abscisic acid as affected by water stress history. Plant Physiol., 65, 455-459.

ALLEN L.H., BOOTE K.J. and HAMMOND L.C., 1975 - Peanut stomatal diffusion resistance affected by soil water and solar radiation. Soil & Crop Sci. Soc. Florida, 35, 42-46.

ALVINO A. and ZERBI G., 1980 - Water status, stomatal resistance and transpiration with relation to different levels of water deficit in maize, tomato, tobacco and sugar beet. Riv. Agron., 14, 210-220.

BOEDT, L.J.J. and LAKER M.C. 1985 - The development of profile available water capacity models. Water Research Commission Rep. 98/1/85. Water Research Commission, Pretoria.

CARBONNEAU A., 1983 - Measurement of gross photosynthesis under natural conditions by using a $^{14}CO_2$ diffucsion porometer. 1. Description of some convenient techniques. Photosynthetica, 17, 235-239.

CATSKY J., CHARTIER P. and DJAVANCHIR A., 1973 - Assmiliation nette, utilisation de l'eau et microclimat d'un champ de mais. IV. Evolution diurne de la resistance stomatique et du deficit de saturation des feuilles; consequences sur la fixation du CO_2. Ann. Agron., 24, 287-305.

CEULEMANS R.J.M., LAKER M.C. and VANASSCHE F.M.G., 1987. Diurnal course of stomatal diffusive conductance and leaf temperature of maize under different irrigation treatments in a semi-arid region. Water Research Commission, Pretoria. 26p.

COWAN I.R., 1977 - Stomatal behaviour and environment. Adv. Bot. Res., 4, 117-228.

DWYER L.M. and STEWART D.W., 1984 - Indicators of water stress in corn (*Zea mays*). Can. J. Plant Sci., 64, 537-546.

HENSLEY M. and DE JAGER J.M., 1982 - The determination of the profile available water capacities of soils. Report by the Dept. Soil Science, University of Fort Hare, Alice, South Africa, 282 p.

JARVIS P.G., 1975 - Water transfer in plants. In : Heat and mass transfer in the biosphere. Vol. I. Transfer processes in plant environment. Eds. DE VRIES D.A. & AFGAN N.H., Scripta Book Co., Washington D.C., 369-394.

JARVIS P.G. and MORISON J.I.L., 1981 - The control of transpiration and photosynthesis by the stomata. In : Stomatal physiology. Eds. JARVIS P.G. & MANSFIELD T.A., Cambridge University Press, Great Britian, 247-279.

JONES, H.G., 1973 - Moderate-term water stresses and associated changes in some photosynthetic parameters in cotton. New Phytol., 72, 1095-1105.

JONES M.B. and MUTHURI F.M., 1984 - The diurnal course of plant water potential, stomatal conductance and treanspiration in a papyrus (*Cyperus papyrus* L.) canopy. Oecologia, 63, 252-255.

JORDAN W.R., BROWN K.W. and THOMAS J.C., 1975 - Leaf age as a determinant in stomatal control of water loss from cotton during water stress. Plant Physiol., 5, 595-599.

KHANNA-CHOPRA R., CHATURVERDI G.S., AGGARWAL P.K. and SINHA S.K., 1980 - Effect of potassium on growth and nitrate reductase during water stress and recovery in maize. Physiol. Plant., 49, 495-500.

KORNER C., SCHEEL J.A. and BAUER H., 1979 - Maximum leaf diffusive conductance in vascular plants. Photosynthetica., 13, 45-82.

MILBURN J.A., 1979 - Water flow in plants. Longman Group Ltd., London, 225 pp.

MIRANDA V., BAKER N.R. and LONG S.P., 1981 - Limitations of photosynthesis in different regions of the Zea mays leaf. New Phytol. 89, 179-190.

OGATA S., SANEOKA H. and MATSUMOTO K., 1985 - Nutrient physiological evaluation of the drought resistance of warm season forage species. 1. Species differences of drought resistance under the field conditions. J.Jpn.Soc.Grassl.Sci., 31, 34-42.

PEARSON C.J., LARSON E.M., HESKETH J.D. and PETERS D.B., 1984 - Development and source-sink effects on single leaf and canopy carbon dioxide exchange in maize. Field Crops Res., 9, 391-402.

SANCHEZ R.A., HALL A.J., TRAPANI N. and DE HUNEAU R.C., 1983 - Effects of water stress on the chlorophyll content, nitrogen level and photosynthesis of leaves of two maize (Zea mays L.) genotypes. Photos. Res., 4, 35-48.

SAWADA S. and SUGAI M., 1984 - Responses of transpiration and CO_2 exchange characteristics to soil moisture stress in four Plantago species. Photosynthetica, 18, 34-42.

SCHOLANDER P.F., HAMMEL H.T., BRADSTREET D. and HEMMINGSEN E.A., 1965 - Sap pressure in vascular plants. Science, 148, 339-346.

VACLAVIK J., 1977 - Distribution pattern of gas exchange in the area of maize leaf blades during the generative phase. Biol. Plant., 19, 457-461.

VACLAVIK J., 1980 - Photosynthesis, transpiration and stomatal conductance in Zea mays leaves as affected by their irradiance at normal and inverse position. Photosynthetica, 14, 482-488.

WHALE, D.M., 1983 - Seasonal variation in the gas exchange characteristics of Primula species. Oegologia, 59, 377-382.

ZUR B. and JONES J.W., 1984 - Diurnal changes in the instantaneous water use efficiency of a soybean crop. Agric. For. Meteorol., 33, 41-51.

a 3.4

TABLE 1 : Environmental and meteorological conditions on the different sampling days at the experimental maize site in Cradock, Republic of South Africa in mid-summer (January, 1986).

January, 1986	21	22	23
Max. temp. (^{o}C)	34.0	22.5	30.4
Min. temp. (^{o}C)	18.6	12.0	7.5
Grass temp. at 08h00 (^{o}C)	14.5	6.8	1.8
Wind speed ($m.s^{-1}$)	4.64	3.09	2.49
A-Pan evaporation (mm)	7.0	9.5	9.0
Sunshine duration (hrs)	7.1	11.8	11.0
Rainfall (mm)	3.0	0.0	0.0

LEGENDS OF FIGURES

Fig. 1. Potential evapotranspiration (PET; calculated by means of a modified Thornwaite water budget equation used in the Department of Agronomy, University of Fort Hare, Alice) and average monthly rainfall (R; 82 years records) for Cradock, Republic of South Africa.

Fig. 2. Soil water content (to a depth of 1.50 m) and rainfall for five different irrigation plots (A, B, C, D and E) of maize at Cradock Experimental Farm, South Africa in mid-summer 1986. Rainfall on the experimental plots is shown by vertical bars above the water contnt curves. Open symbols represent stressed plots; closed symbols represent unstressed plots. Soil water profile lines at field capacity (FC) and first material stress (FS) are included for reference purposes.

Fig. 3. Soil water patterns for stressed (plots A and B) and unstressed (plots D and E) maize plots in an Inceptisol soil measured with a neutron hydroprobe on January 23, 1986 at Cradock Experimental Farm, South Africa. Field capacity (to a depth of 1.5 m) : 475 mm. PAWC at flowering : 151 mm.

Fig. 4. Diurnal courses of environmental factors on three consecutive measuring days.

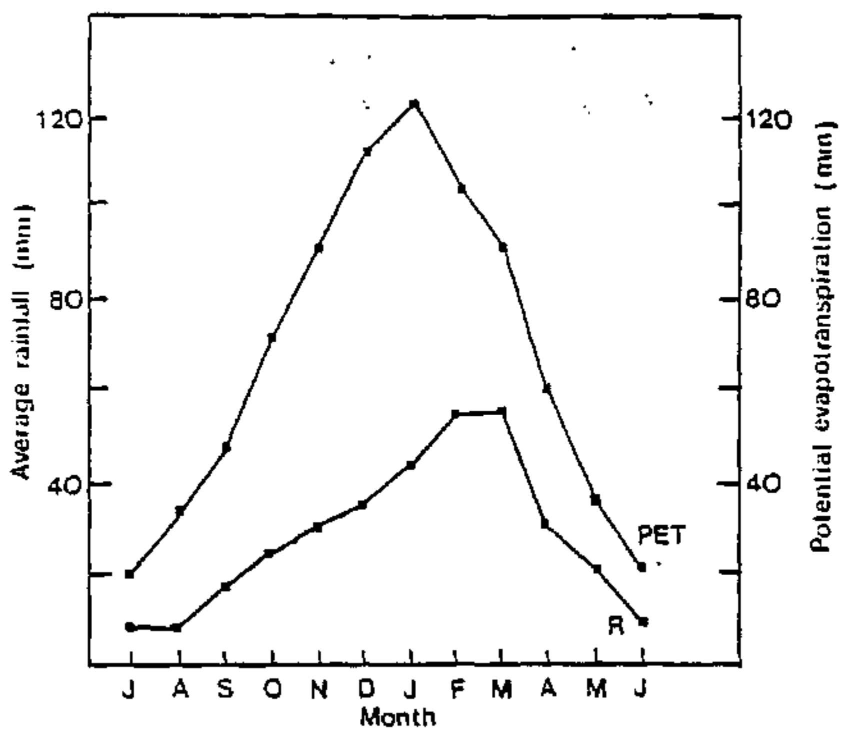
Fig. 5. The response of stomatal conductance to photosynthetically active radiation incident on the maize leaf surface for unstressed plants on a specific measuring day (January 21, 1986). Each point represents the mean of four measurements. Vertical bars represent standard error of mean.

Fig. 6. Stomatal conductance values for stressed and unstressed maize plants respectively at three different times of the day on three consecutive measuring days.

Fig. 7. Effects of increasing soil water stress on stomatal diffusion conductance of mature maize at midday in mid-summer. Each point is the mean of five measurements. Vertical bars represent standard error of mean.

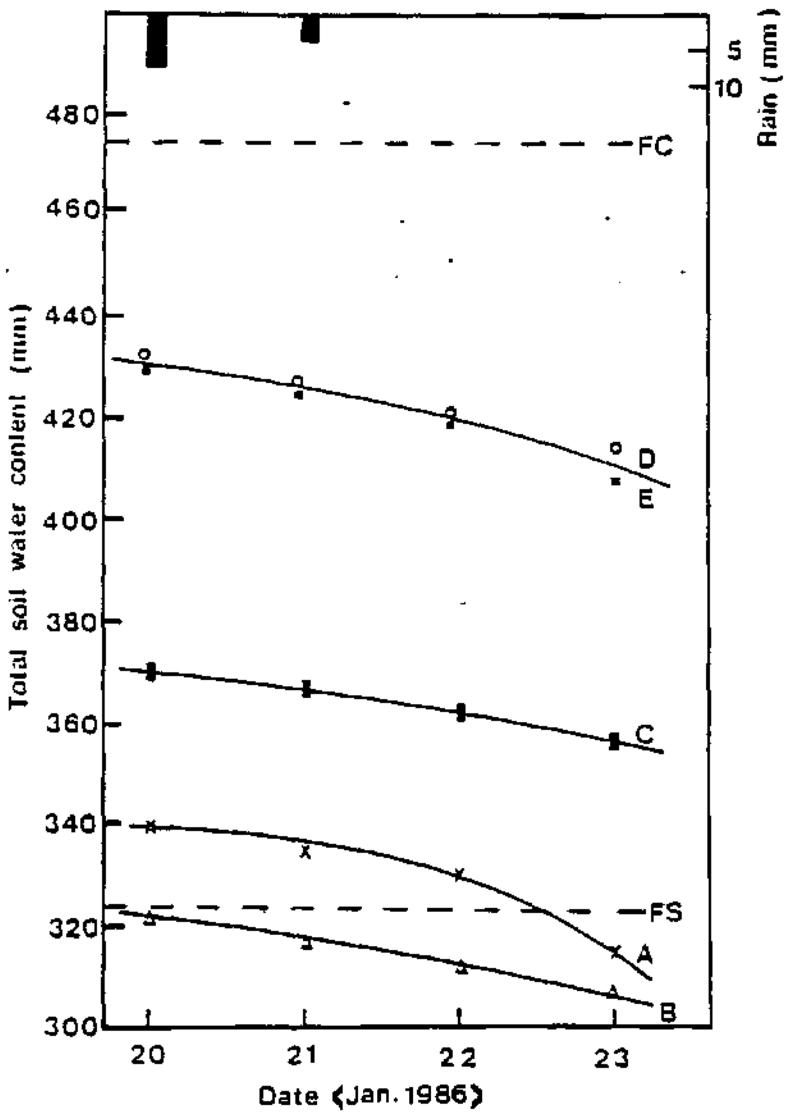
Fig. 8. Mean early morning and late afternoon stomatal conductance values as a function of VSD on three consecutive measuring days.

Fig. 9. Xylem water potential values for stressed and unstressed maize plants respectively at three different times of the day on three consecutive measuring days.



Average rainfall (mm)
Potential evapotranspiration (mm)
120
80
40
PET
R
J A S O N D J F M A M J
Month

FIG. 1



480
460
440
420
400
380
360
340
320
300
Total soil water content (mm)
FC
FS
D
E
C
A
B
5
10
Rain (mm)
20
21
22
23
Date (Jan. 1986)

FIG. 2

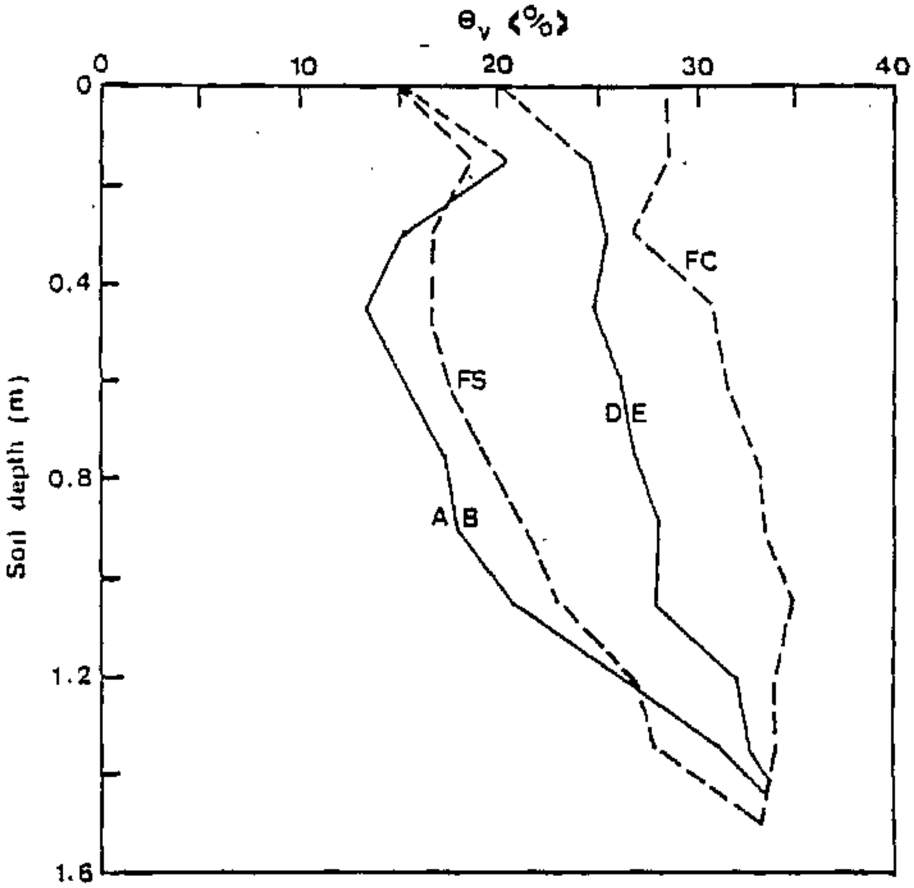


FIG. 3

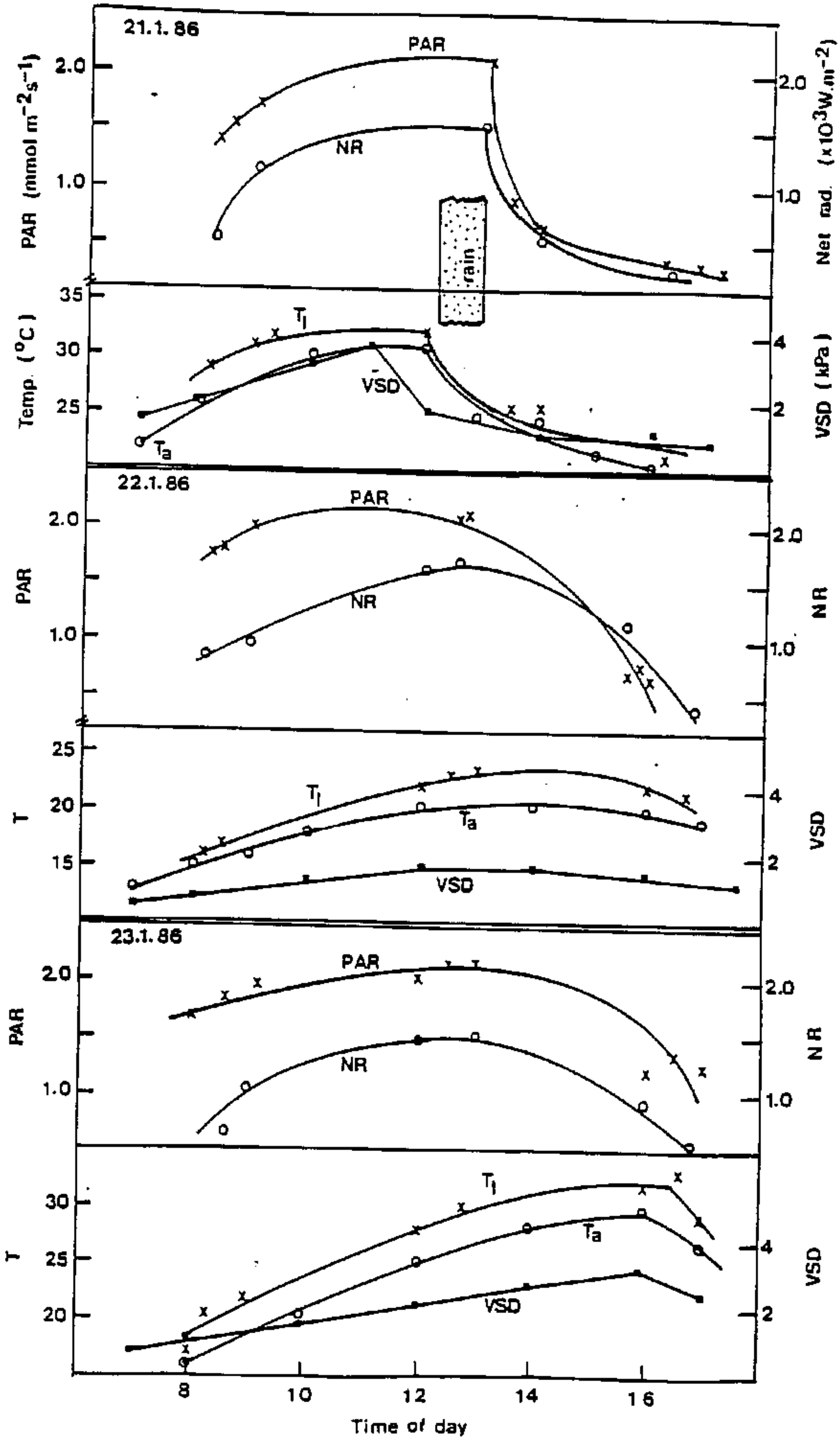

21.1.86
PAR
NR
rain
PAR (mmol m^{-2}s^{-1})
Net rad. (x10^{3}W.m^{-2})
Temp. (^{o}C)
VSD (kPa)
T_l
VSD
T_a
22.1.86
PAR
NR
T_l
T_a
VSD
T
23.1.86
PAR
NR
T_l
T_a
VSD
T
Time of day

FIG. 4

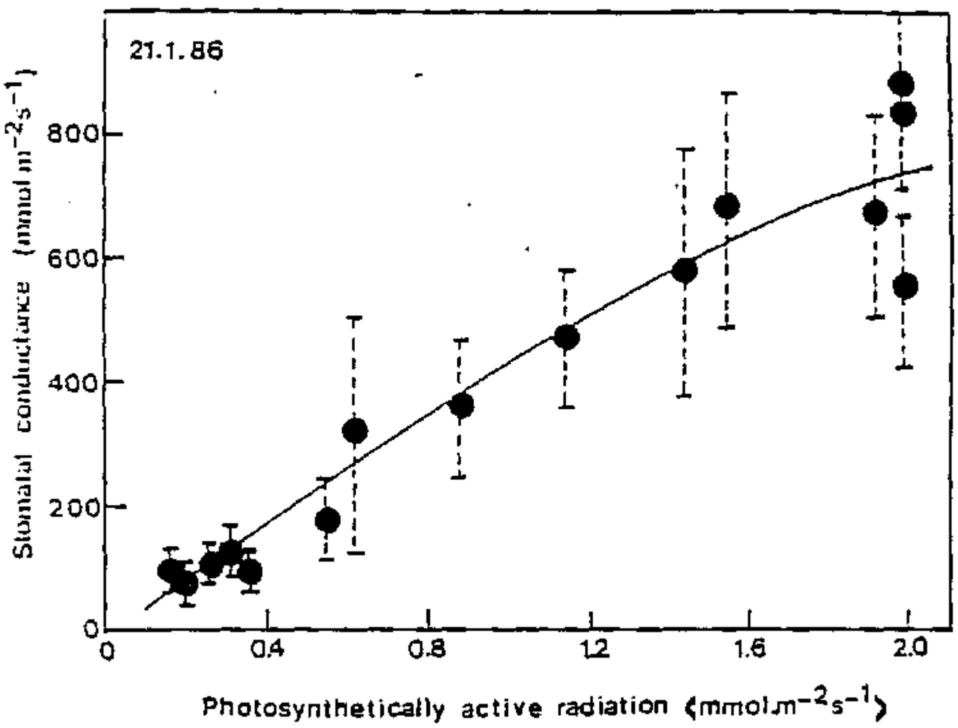
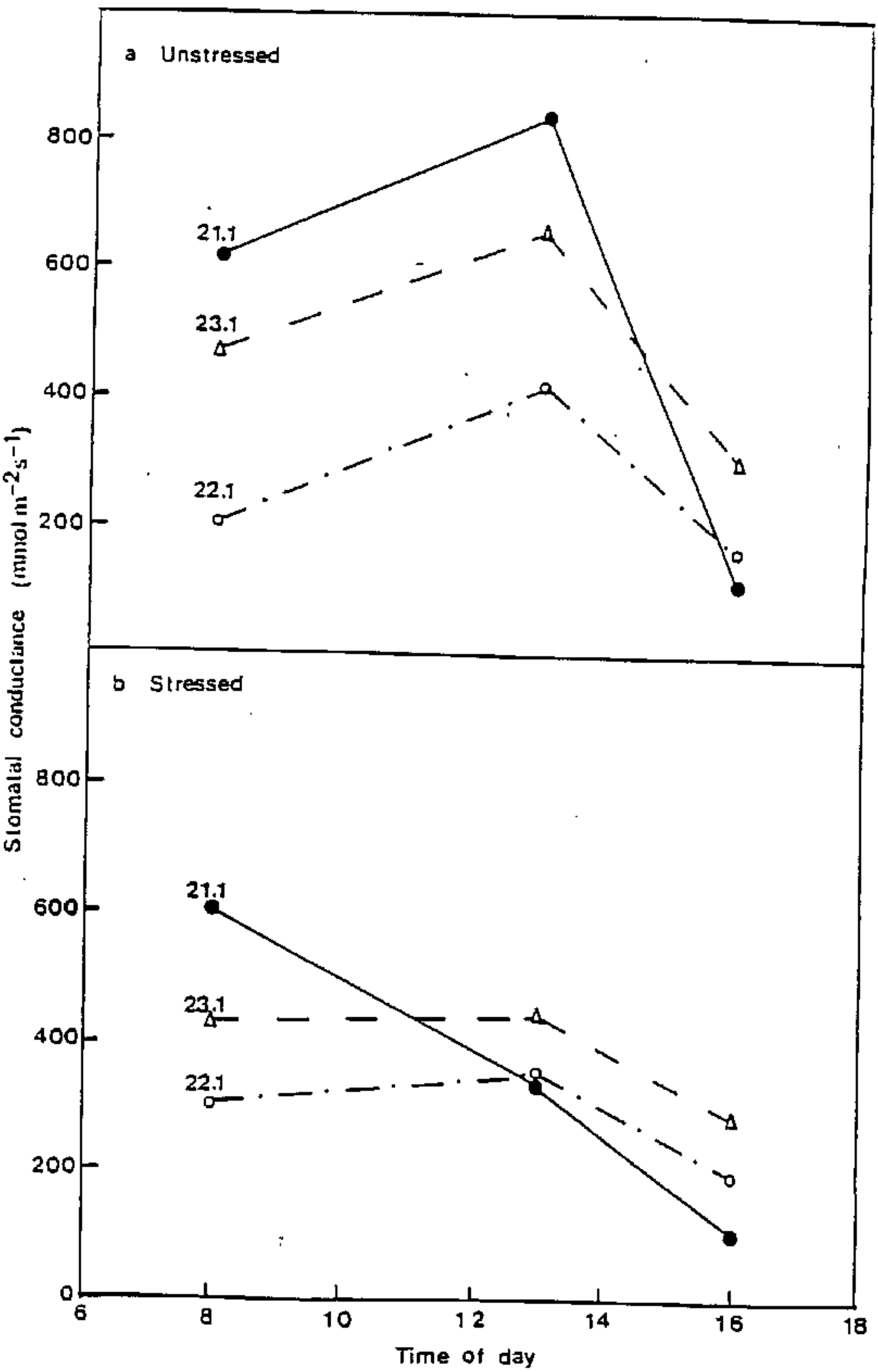

21.1.86
Stomatal conductance (mmol m^{-2}s^{-1})
0
200
400
600
800
0
0.4
0.8
1.2
1.6
2.0
Photosynthetically active radiation (mmol.m^{-2}s^{-1})

FIG. 5



a Unstressed
b Stressed
21.1
23.1
22.1
800
600
400
200
0
Stomatal conductance (mmol m^{-2}s^{-1})
6
8
10
12
14
16
18
Time of day

FIG. 6

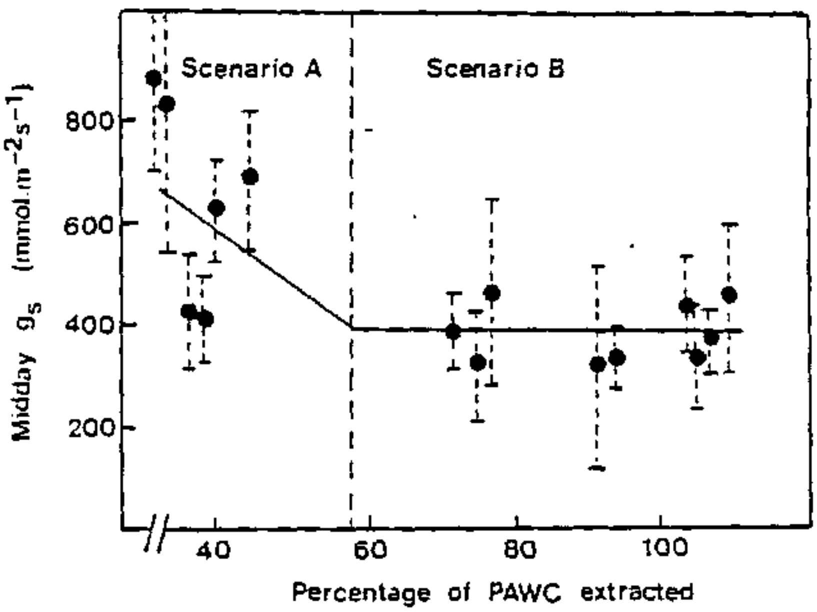

Scenario A
Scenario B
Midday g_s (mmol.m^{-2}s^{-1})
800
600
400
200
40
60
80
100
Percentage of PAWC extracted

FIG. 7

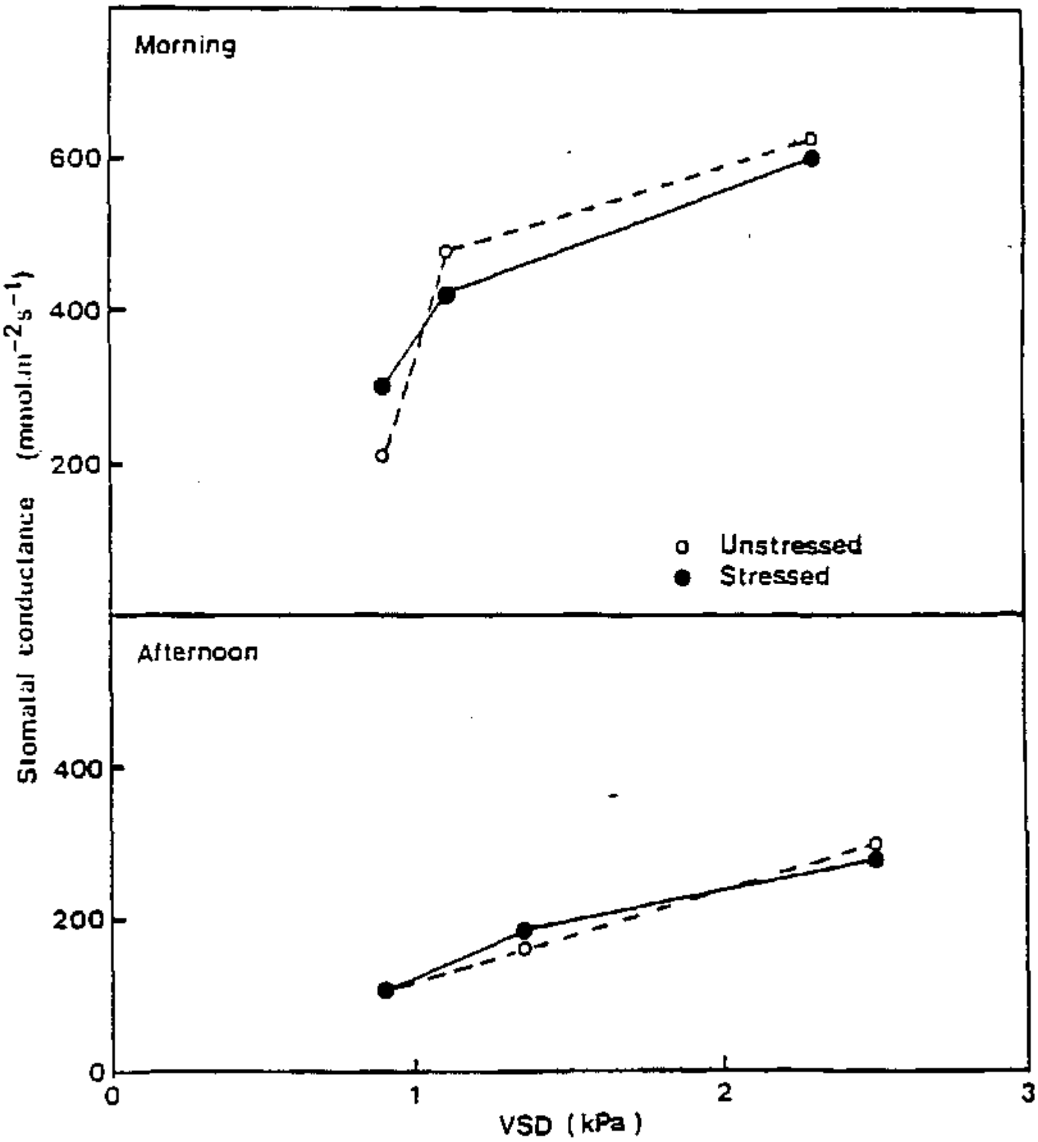

Morning
Afternoon
Stomatal conductance (mmol.m^{-2}s^{-1})
600
400
200
0
Unstressed
Stressed
0
1
2
3
VSD (kPa)

FIG. 8

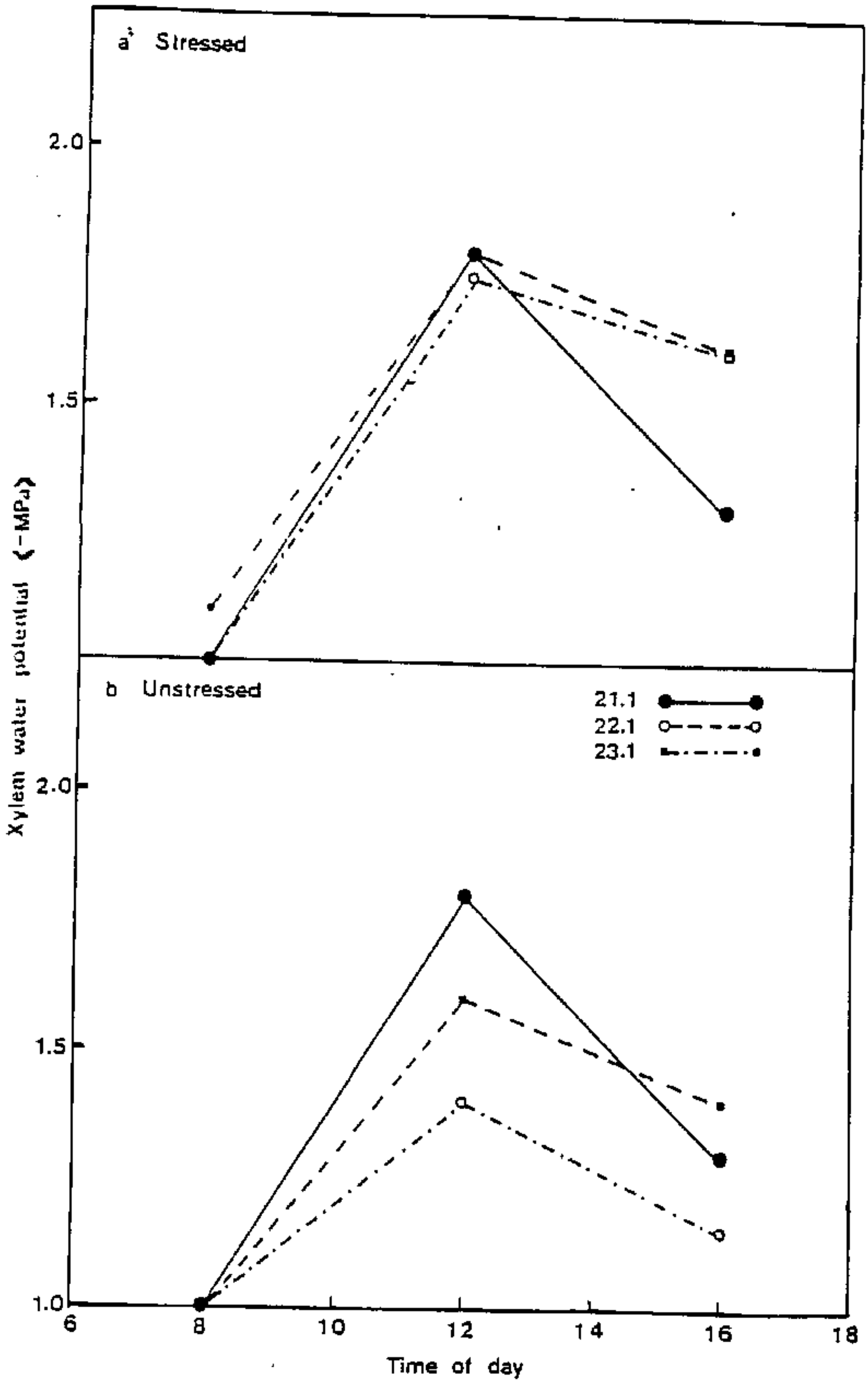

a Stressed
b Unstressed
21.1
22.1
23.1
Xylem water potential (-MPa)
2.0
1.5
1.0
6
8
10
12
14
16
18
Time of day

FIG. 9

APPENDIX 4.1.1 YIELD, APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH WHEAT AT SITE ISO-A (1985 WINTER SEASON)

Treatments					
25	50	75	100	125	def
yield (ton/ha)					
2.43(4)	2,96(2)	3,06(1)	2,69(6)	2,65(5)	2,92(3)
2,35(15)	2,58(10)	2,30(13)	2,16(14)	2,88(7)	2,94(8)
2,34(16)	3,59(19)	3,21(21)	3,29(23)	3,00(9)	3,24(18)
3,28(22)	3,11(24)	2,86(27)	3,21(25)	3,22(17)	3,53(20)
cv (%)					
17,5	13,6	13,9	18,5	8,1	9,1
applied water (mm)					
690	610	640	540	540	560
rain (mm)					
245	245	245	245	245	245
soil water deficit at harvest (mm)					
10	10	20	65	75	45
total water consumption (mm)					
945	865	905	850	860	850
rain/total consumption (%)					
26	28	27	29	28	29

numbers between brackets indicate the plot number.

APPENDIX 4.1.2 YIELD, APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH WHEAT AT SITE ISO-B (1986 WINTER SEASON)

Treatments

control	50-75	25-100	50-100	75-100	100yg-50
		yield (ton/ha)			
5.54(2)	4.33(5)	4.23(11)	4.41(1)	4.44(8)	4.90(7)
4.[illegible](4)	4.68(10)	4.99(14)	5.06(19)	3.45(20)	4.97(16)
6[illegible](18)	5.34(13)	3.72(26)	3.98(24)	3.11(23)	5.06(22)
4.[illegible](27)	5.21(32)	4.98(31)	4.18(28)	4.80(33)	5.08(30)
		cv (%)			
12.9	9.6	13.8	10.6	20.3	1.7
		applied water (mm)			
510	490	355	375	385	530
		rain (mm)			
120	120	120	120	120	120
		soil water deficit at harvest (mm)			
60	100	105	90	100	50
		total water consumption (mm)			
690	710	680	585	595	700
		rain/total consumption (%)			
17	17	21	21	20	17
		number of irrigations			
8	8	7	6	5	7

numbers between brackets indicate the plot number.

APPENDIX 4.1.3 YIELD. APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH DURUM WHEAT AT SITE ISO-B (1986 WINTER SEASON)

Treatments		
control	50-75	50-100
	yield (ton/ha)	
4,59(3)	3,57(12)	4,32(6)
4,79(15)	4,55(17)	3,71(9)
4,86(29)	4,24(25)	4,99(21)
	cv (%)	
2,9	12,2	14,7
	applied water (mm)	
440	430	500
	rain (mm)	
120	120	120
	soil water deficit at harvest (mm)	
90	65	100
	total water consumption (mm)	
650	615	720
	rain/total consumption (%)	
18	20	17
	number of irrigations	
8	8	8

numbers between brackets indicate the plot number.

APPENDIX 4.1.4 YIELD, APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH WHEAT AT SITE ISO-A (1987 WINTER SEASON)

Treatments

control	100t	125t	100tf	125tf	100b	125b
yield (ton/ha)						
5,86(3)	4,08(16)	6,20(5)	4,57(1)	4,96(2)	6,36(6)	4,23(4)
4,87(9)	5,47(21)	6,71(11)	5,89(8)	5,48(7)	5,46(13)	3,92(10)
6,24(20)	5,71(24)	4,93(14)	6,85(12)	3,83(19)	4,69(17)	3,41(18)
5,67(25)	6,21(28)	4,60(27)	5,30(15)	4,43(26)	6,11(22)	
cv(%)						
10,2	17,0	18,0	17,1	15,0	13,2	10,8
applied water (mm)						
425	375	375	325	275	325	275
rain (mm)						
160	160	160	160	160	160	160
soil water deficit at harvest (mm)						
50	35	40	50	20	50	70
total water consumption (mm)						
635	570	575	535	455	535	505
rain/total consumption (%)						
25	28	28	30	35	30	32
number of irrigations						
8	6	6	5	4	5	5

numbers between brackets indicate plot number.

APPENDIX 4.1.5 YIELD, APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH MAIZE AT SITE ISO-B (1985-1986 SUMMER SEASON)

Treatments

25	50	75	100	125	def
yield (ton/ha)					
9,70(2)	9,95(3)	8,92(4)	8,66(7)	8,43(6)	8,60(5)
10,80(14)	8.30(8)	9,16(9)	8,43(10)	8,49(11)	9,86(15)
9,88(19)	11,50(13)	10,10(12)	10.27(16)	9,82(17)	9,37(18)
11,11(25)	9,65(20)	8,66(21)	11,73(26)	8,07(29)	8,40(22)
cv (%)					
6.6	13.3	6,8	15,8	8,8	7,5
applied water (mm)					
520	585	555	515	430	385
rain (mm)					
250	250	250	250	250	250
soil water deficit at harvest (mm)					
90	115	125	115	130	135
total water consumption (mm)					
860	950	930	880	810	770
rain/total consumption (%)					
29	26	27	28	31	32
number of irrigations					
12	9	8	7	6	7

numbers between brackets indicate the plot number.

APPENDIX 4.1.6 YIELD, APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH MAIZE AT SITE ISO-DAMBLOK (1986-1987 SUMMER SEASON).

Treatments

control	30-50	30-75	50-75	75-75	75-100
yield (ton/ha)					
7,80(4)	9.34(5)	7,41(2)	9.21(6)	9.17(3)	7,91(10)
9.24(7)	8.69(19)	7.46(9)	9,46(11)	8,55(8)	9,70(12)
8,39(14)	8.46(20)	9,38(13)	6,56(17)	8,63(15)	7.07(16)
7,93(18)	7.28(28)	8,13(22)	6,83(24)	9,06(23)	7.31(21)
cv (%)					
7.8	10.2	11.3	19.1	3.5	14.9
			1.9*		
applied water (mm)					
625	715	635	700	825	755
rain (mm)					
190	190	190	190	190	190
soil water deficit at harvest (mm)					
150	155	175	165	145	175
total water consumption (mm)					
965	1060	1000	1055	1160	1120
rain/total consumption (%)					
20	18	19	18	16	17
number of irrigations					
12	13	12	10	10	9

* for plots 5 and 10 only, plots 16 and 23 were not used in the statistical analysis.
numbers between brackets indicate the plot number.

APPENDIX 4.1.7 YIELD, APPLIED WATER AND TOTAL WATER CONSUMPTION FOR THE DIFFERENT IRRIGATION TREATMENTS WITH MAIZE AT SITE ISO-B (1987-1988 SUMMER SEASON)

Treatments

control	100-4	125-4	100-10
yield (ton/ha)			
10,77(3)	9,32(1)	9,54(2)	10,55(4)
9,38(9)	9,90(7)	9,72(8)	9,25(12)
12,74(20)	11,35(18)	10,06(19)	8,98(16)
8,59(25)	9,57(23)	8,50(24)	9,95(29)
cv (%)			
17.5	9,0	7,1	7,3
applied water (mm)			
525	525	450	475
total water consumption (mm)			
825	840	720	800
number of irrigations			
10	9	8	8

Treatments

125-10	100-15	125-15	50-75
yield (ton/ha)			
8,79(6)	9,32(11)	8,77(10)	8,70(5)
10,62(13)	12,73(14)	7,48(22)	12,12(15)
8,73(17)	8,62(28)	5,80(26)	9,76(21)
7,87(31)	9,27(32)	10,17(30)	7,46(27)
cv (%)			
12,9	18,6	23,1	20,8
applied water (mm)			
450	525	475	525
total water consumption (mm)			
800	800	770	855
number of irrigations			
7	8	7	8

numbers between brackets indicate the plot number.

APPENDIX 5.1 ELECTRICAL RESISTANCE AND AMOUNT OF SOLUBLE CALCIUM, MAGNESIUM, POTASSIUM AND SODIUM IN TOP- AND SUBSOIL FOR EACH TREATMENT AT SITE ISO-A (1987-1988 SEASON)

Treatment	1	2	3	4	5	6	7
Plot 27							
topsoil							
R (Ohm)	750	920	800	630	850	750	900
Ca (mg/kg)	2632	2530	2840	2434	2878	2934	3012
Mg (mg/kg)	750	742	714	732	718	608	642
K (mg/kg)	244	222	248	210	244	266	220
Na (mg/kg)	186	154	162	136	138	142	108
subsoil							
R (Ohm)	420	650	550	730	550	730	900
Ca (mg/kg)	2888	2956	2768	2886	2800	2780	2864
Mg (mg/kg)	824	808	712	966	730	850	808
K (mg/kg)	256	182	140	140	128	186	220
Na (mg/kg)	1022	576	968	422	868	370	200
Plot 28							
topsoil							
R (Ohm)	400	600	650	740	670	900	900
Ca (mg/kg)	2878	2538	3022	2966	2724	2436	2750
Mg (mg/kg)	1154	796	890	946	796	870	876
K (mg/kg)	270	274	300	276	296	216	252
Na (mg/kg)	338	204	182	208	162	168	124
subsoil							
R (Ohm)	300	300	500	550	630	560	1000
Ca (mg/kg	1720	2466	2624	2874	2820	2538	2608
Mg (mg/kg)	812	660	812	820	1000	852	1088
K (mg/kg)	134	130	136	136	188	156	218
Na (mg/kg)	1644	1400	856	788	552	804	190