RESPONSE OF POTATO GENOTYPES TO DIFFERENT IRRIGATION WATER REGIMES

by

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EXECUTIVE SUMMARY

The potato is an important source of food world wide. In South Africa the crop is primarily produced under irrigation (about 73% of the total area under potatoes) for the fresh market, for the processing industry as chips and crisps, and for seed potatoes.

In subtropical climates potato crops are often subjected to unfavourable conditions of high temperatures and water shortages during the growing season: heat- and water stress adversely affect growth, tuber yield and quality. In these hot, dry climates the high evaporative demand increases crop water requirements, which may compound the sensitivity of the crop to water stress, resulting in greater yield reductions than experienced with similar water deficits under cooler conditions.

Due to limited water resources and unreliable annual distribution of rain, water stress is a major constraint on potato production in South Africa. In some production areas the quantity and quality of water resources have deteriorated badly due to over exploitation. Two possible approaches could be followed by agriculture to achieve savings on water use without reducing the cultivated area. The first option is to cut down on current water use by the application of sound irrigation scheduling techniques as it has been shown that, although water stress is considered an important production limiting factor, only a few producers apply scheduling on irrigated crops. The negative attitude towards irrigation scheduling can be attributed to various factors. The lack of easy, quick and reliable scheduling methods seems to be one of the major reasons. The second option is to breed and select genotypes that are more efficient with regard to water use characteristics, which may be a long term solution to the problem. This alternative is well recognized for many crops and breeding for better adaptability to drought is an important objective of the local potato breeding programme at Roodeplaat.

Since little is known about the amounts of water required for optimum production and the effects of water stress on local potato genotypes, the following objectives were set to clarify these aspects:

1. To determine the water use of the most important potato cultivars and breeding lines to ensure maximum yield and quality.
2. To identify the critical growth stages of potatoes to water stress.
3. To determine the effect of water stress imposed in different growth stages on growth and development.
4. To determine the suitability of some physiological parameters to indicate the existence of plant water stress and to serve as early screening methods for drought tolerance in potato genotypes.
5. To use collected data for the development of crop growth models and adapt irrigation scheduling models for potatoes.

Seven trials were conducted from the 1992 autumn planting until the autumn of 1995. The trials were planted under automated rain shelters and irrigation booms were used in combination with rain shelters.

Genotypic yield differences in response to levels of water stress were mainly confined to the spring plantings, when temperatures and the atmospheric evaporative demand are higher than in autumn. Some genotypes were clearly more adapted to water-stress conditions than others. Of the late genotypes Late Harvest and Mnandi performed best at the dry treatments, while Mnandi had the highest yields at the wetter treatments as well. The findings of this study contrast the suggestions of Jefferies & MacKerron (1993) that there is limited capacity for improved drought tolerance through breeding other than improving the yield potential. Genotypes such as Late Harvest, Vanderplank, 82-252-1 and 83-252-1 had low yield potentials under favourable conditions, but had of the highest yields when they were water-stressed.

The ranking of genotypes according to yields attained at different water treatments is an important contribution to the current state of knowledge and will be valuable to producers in assisting them to select genotypes most suitable to their specific growing conditions. The ranking order of genotypes as a result of water treatments only changed in spring plantings, indicating that in autumn genotypes can be selected purely according to yield potential or specific needs of the end user. If producers have a choice between spring and autumn planting seasons, the range of high-yielding genotypes to select from will be larger for the autumn planting. High yields can usually be expected from autumn plantings, while the saving on irrigation water will be substantial, compared to a spring planting.

Local potato genotypes were for the first time characterised according to drought tolerance. Drought-tolerant genotypes were regarded as those that showed the lowest reduction in tuber yield when exposed to water stress. Mnandi, Late Harvest, Vanderplank, 82-252-5 and 83-252-1 were the most drought tolerant of the genotypes evaluated. Genotypic differences in drought tolerance were less pronounced in autumn, because temperatures and atmospheric evaporative demand were lower. The drought-sensitivity index demonstrated in this study should be a valuable tool to plant breeders for the selection of drought-tolerant parental material in breeding programmes.

The negative effect of water stress on tuber size was most severe in spring plantings, when temperatures and the atmospheric evaporative demand were higher. The yield of medium and especially large tubers were damaged by water stress, but genotypes within the same trial did not respond differently to water stress.

Water regimes apparently had less effect than temperature on tuber internal quality in spring plantings. The effect of water regimes on tuber quality was not clear and, contrary to most reports in literature, no negative effects of water stress on tuber relative density and chip colour could be demonstrated in spring plantings, while chip colour improved as a result of water stress in autumn plantings. Firstly, the contradictory results are possibly attributable to the dominating effects of temperature on tuber quality. Secondly, the irrigation boom method used does not resemble field conditions, due to the regular application of small amounts of water to dry treatments.

Part one of the first objective, which was to determine the water regimes that will ensure maximum yield and quality of different potato genotypes, were only partly reached: although the intermediate regimes (W2 and W3) seemed to provide the most favourable compromise

between highest yield and best quality, genotypic differences could not be identified. The irrigation boom system used is probably to be blamed for the fact that possible genotypic differences could not be found.

Photosynthetic rate (Pn) and stomatal resistance (Rs) were investigated as indicators of drought tolerance. Tuber yields correlated well ($r=0.87$ to $r=0.99$) with seasonal mean values of both these parameters for all the genotypes, but the regression functions that describe these relationships changed for seasons and genotypes. The magnitude of decline in Pn or increase in Rs in response to drought was found to be related to the magnitude of decline in tuber yield. These relationships are, however, not valid for heat-sensitive genotypes such as Up-to-date. These findings may be a significant contribution to early selection techniques for drought tolerance in crops, but the technique should be evaluated on independent data and on a wider range of more diverse material to prove its usefulness.

The objective of finding suitable physiological parameters as indicators of water stress and to serve as early screening methods for drought tolerance in potatoes was reached, since the regression functions obtained from this study can in future be used to estimate the expected yield reduction of a specific genotype, once the reduction in Pn or increase in Rs for that genotype is established.

The vast differences in total water use between plantings and years were mainly as a result of differences in atmospheric evaporative demand. Normalising the water-use data for seasonal vapour pressure deficits narrowed the gap between years, but differences between spring and autumn plantings were still evident for the same genotypes. The reason for the remaining differences should probably be attributed to the fact that evapotranspiration and not transpiration data was used for comparison.

The small differences observed between genotypes in water use can perhaps be explained by the way water use was calculated and by the method of irrigation used. Water use was mainly a function of water applied, as genotypes within the same maturity class received the same amount of water. Since genotypic differences in water use could not be determined with the irrigation method used, this second part of the first objective was not reached, as we are not sure that genotypic differences in water requirements were not present. The irrigation boom system is therefore not ideal for water use studies, although it is a valuable technique for drought tolerance screening.

Water-use efficiencies were the highest for autumn plantings, because less water was lost through evaporation without contributing to the production of dry matter. Highest water-use efficiencies were generally recorded at the intermediate treatments (W2 and W3) for both plantings. The high-potential cultivars Up-to-date, BP1, Mnandi, 81-163-40 and Mondial had the highest efficiencies in autumn plantings, independent of the water treatment applied, but in spring plantings the water-use efficiencies of genotypes were influenced by water treatments. Generally, Up-to-date, and 83-363-67 had the highest efficiencies at the wet to intermediate treatments, while the more drought-tolerant genotypes Vanderplank, Late Harvest and Mnandi had high efficiencies at all the water treatments in spring plantings. The medium-maturity genotypes 82-252-5 and 83-252-1 had the highest efficiencies at the driest treatments.

Rooting density in deep soil layers was not related to drought tolerance for the genotypes studied. Although root distribution was slightly changed by water regime, root development does not seem to be a suitable indicator of drought tolerance in potato genotypes. The majority of roots were located in the top 600 mm soil layer for all potato genotypes. The greatest portion of soil water was also extracted from this zone, which is suggested as the maximum rooting depth for irrigation scheduling calculations.

The Soil Water Balance model (SWB) was calibrated for the cultivar Up-to-date, using data sets of autumn plantings. SWB generally performed satisfactorily with regard to the simulation of dry matter production and water deficit of the soil profile for both well-watered and water-stressed conditions in autumn plantings. Simulations of crop growth and soil-water depletion were, however, not accurate in spring if the crop parameters determined for autumn plantings were used. Canopy size was under estimated and the date of senescence was too early, resulting in incorrectly simulated soil-water deficits. The reason for the poor results in spring plantings is probably attributable to the fact that the effects of photoperiod and high

temperatures on development and assimilate distribution is not taken into account by the generic crop model. The model therefore needs further refinement to ensure better simulations of canopy development over seasons, possibly by accommodating the effect of day-length on growth, development and senescence. Alternatively, separate crop parameters should be determined for spring or summer plantings. Crop parameters should also be established for cultivars of other maturity classes, which will require complete growth analysis studies.

The objective to use data collected in this study for the development or adaptation of a simulation model for irrigation scheduling purposes was reached for the cultivar Up-to-date, a medium-maturity cultivar. Destructive growth analyses were not possible because of the limited number of plants that could be accommodated under the rain shelters. Sufficient crop data were therefore not available for the determination of crop parameters for specific genotypes. If the water requirements of genotypes within the same maturity class do not differ, as suggested by the results of this study, the first important step in future research would be to obtain crop parameters for the most important genotypes belonging to the early and late maturity classes. In spite of the research still needed to improve the model, it should already be a valuable tool which could assist both advisors and potato producers on a daily basis to decide when and how much to irrigate their potato crops.

A part of the first objective was to determine the water requirements for optimal production of different genotypes. The water use of genotypes within the same maturity class did, however, not differ, possibly due to the equal amounts of water applied to all the genotypes for the same water regime. It is therefore not known whether total water use would have been different if another method of irrigation was used instead of the irrigation boom.

The objectives set to determine the effects of water stress imposed in different growth stages on growth and development, and therefore the identification of critical growth stages, were not met in this study. Different levels of water stress could not be imposed at different growth stages, because the irrigation boom did not permit such treatments.

Reports from literature indicate the main effects of drought on growth and development to be

the following: Drought usually reduces the canopy size, whereby the interception of solar radiation is reduced. Secondly, crop development and canopy senescence are hastened, which result in a shortened life cycle. Water stress during the tuber initiation phase will result in less tubers being initiated and therefore the potential yield is reduced. The most devastating effect of water stress on tuber yield is during the tuber bulking phase: drought reduces the number of harvestable tubers by reducing the number of tubers that grow into a certain minimum size. The downward shift in tuber size distribution result in a lower total yield.

Water supply may also have adverse effects on tuber internal quality. Tuber relative density and reducing sugar content are the two quality characteristics commonly affected by water supply. Tuber relative density is usually enhanced by water stress late in the growing season, while reducing sugar content will rise as a result of late water stress, resulting in unacceptably dark chip colours.

Recommendations for future water use studies on potatoes include the following: if the water requirements of individual genotypes are to be established, the irrigation boom should deliberately not be used, for the reasons already elaborated on in this section. These also apply to studies for determining the effect of water levels on tuber internal quality. The irrigation boom technique is, however, ideal when genotypes are to be screened for drought tolerance. The suitability of photosynthetic rate and stomatal resistance as early screening methods for drought tolerance should be evaluated on independent data sets before being applied. The SWB irrigation scheduling model should be refined to enable its use in any season. Crop parameters should also be established for potato cultivars of other maturity classes.

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CHAPTER 1

GENERAL INTRODUCTION

The potato is an important source of food in countries world wide. This is also the case in South Africa, where potatoes are the most important vegetable crop. During the 1995 production season for example, potatoes were cultivated on about 56 000 ha (Potato Producers' Organisation (PPO), 1995). About 73% of the potato production area in South Africa is under irrigation. Production is for the fresh market, the processing industry and for seed potatoes.

Potato crops in subtropical climates are often subjected to heat and water stress due to unfavourable conditions of high temperatures and water shortages during the growing season, which adversely affect growth, tuber yield and quality (Coleman, 1986; Levy, Genizi & Goldman, 1990; Miller & Martin, 1990). According to Trebejo & Midmore (1990), in such hot, dry climates the high evaporative demand will increase crop water requirements, which may compound the sensitivity to water stress, resulting in greater yield reductions than experienced with similar water deficits under cooler conditions.

Due to limited water resources and the unreliable annual distribution of rain, water stress also is a major constraint on potato production in South Africa (Mould & Rutherfoord, 1980). In the Northern Province, for example, which is the largest potato-producing area in the country (PPO, 1995), producers are entirely dependent on underground water resources for their irrigation needs. The continuous lowering of the water table during the early nineties has been a major source of concern to producers in that area. Water quality has also deteriorated during the last decade, making it almost unusable for potato irrigation.

In South Africa there is a growing need for water on the domestic and industrial fronts, and the agricultural sector will be obliged to use water with more care in future. At least two approaches could possibly be followed to achieve water-use savings without reducing the cultivated area. The first would be to cut down on current water use by the application of sound irrigation scheduling techniques. Surveys carried out among potato producers by the PPO have shown that irrigation management is considered an important production limiting factor. From another survey (Annandale, Van der Westhuizen & Olivier, 1996) it is, however, also evident that only a few producers do apply scheduling techniques to irrigated crops. Although yield is not determined solely by water supply, the general lack of appropriate irrigation management is emphasized by the fact that the average yield from irrigated potato crops in South Africa amounts to 28 t ha^{-1}, compared to yields of 70 t ha^{-1} and higher achieved through good management, including effective irrigation scheduling. The negative attitude of potato growers to irrigation scheduling can be attributed to various factors, but the lack of easy, quick and reliable scheduling methods seems to be an important reason why farmers do not manage irrigation effectively.

Although effective irrigation scheduling may increase water savings in the short-term, the breeding and selection of genotypes that are more efficient with regard to water-use characteristics may be a second and long-term alternative to the problem. This is a well-recognized alternative for the potato, as for many crops (Cother, Hocking & Logan, 1981; Chaudhuri, Deaton, Kanemasu, Wall, Macrarian & Dobrenz, 1986; Kvien & Branch, 1988; Pennypacker, Leath, Stout & Hill, 1990; Trebejo & Midmore, 1990; Ekanayake & Midmore, 1992). Breeding for better adaptability to drought is therefore also an objective of the local potato breeding programme at Roodeplaat.

Since little is known about the water requirements and drought tolerance characteristics of local potato germplasm, the objectives of this study were:

(1) To determine the water use of the most important potato cultivars and breeding lines to ensure maximum yield and quality.
(2) To identify critical growth stages of potatoes to water stress.
(3) To determine the effect of water stress imposed in different growth stages on growth and development.
(4) To determine the suitability of some physiological parameters to indicate the existence of plant water stress and to serve as early screening methods for drought tolerance in

potato genotypes.

(5) To use collected data to develop crop growth models and adapt irrigation scheduling models for potatoes.

In the first two data chapters of this report (Chapters 4 and 5) the effects of water stress on tuber yield, size distribution and internal tuber quality are investigated. Chapter 6 investigates the suitability of two physiological parameters, photosynthetic rate and stomatal resistance, to serve as indicators of water stress and drought tolerance in potatoes. The effect of water regimes on water use, water-use efficiencies and root distribution of different genotypes are studied in the following two chapters. In Chapter 9 the genotypes included in this study are classified according to drought tolerance. The last data chapter elaborate on the calibration and evaluation of a simulation model for the irrigation scheduling of potatoes.

The identification of critical growth stages, as well as the effects of water stress on growth and development were not attainable in this study. The main reason being the fact that plots cannot be irrigated separately when the irrigation boom is used. Therefore differential stress levels could not be applied to different plots for different growth stages. This fact was realised at the initial stages of the project and the project team was advised by the steering committee to obtain the current state of knowledge in this regard from literature. In the literature survey (Chapter 2) the effects of water stress in different growth stages of the potato crop are discussed according to reports in the literature.

CHAPTER 2

LITERATURE REVIEW

Water stress is recognized as a major constraint on potato production world-wide (Schapendonk, Spitters & Groot, 1989), with significant tuber-yield reductions being the most important outcome. It is often stated that the potato plant is very sensitive to water stress and that good yield and quality can only be achieved with a sufficient and regular supply of water (Doorenbos & Kassam, 1979; Mould & Rutherfoord, 1980; Van Loon, 1981).

The sensitivity of the crop to water stress can be attributed to many factors, one being that the onset of stress is associated with mild shortages in soil-water supply. It has been shown that the stomata of potato plants start to close at relatively high water potentials, compared to other crops (potato: -350 kPa, soybean: -1100 kPa and cotton: -1300 kPa) (Van Loon, 1981). According to Van Loon (1981), stomatal closure results in decreased transpiration and photosynthetic rates that will have a negative influence on the production of dry matter. Another factor may be the potato plant's shallow and poorly distributed root system. Doorenbos & Kassam (1979) state that potato plants extract about 70% of their water requirements from the upper 300 mm of soil and 100% from the upper 400 to 600 mm. Fulton (1970) reported that potato yield was restricted by a relatively small stress applied to only a portion of the root system, which suggests that potato roots may have a relatively low capacity for water absorption and that almost the total root system must have access to readily available water in order to produce maximum yield.

Authors' opinions differ greatly with respect to the permissible depletion of soil water before the onset of irrigation. According to Fulton (1970), potato yield is limited by soil-water potentials lower than -50 kPa in the upper 150 mm soil layer, while Mould & Rutherfoord (1980) have suggested potentials between -50 and -70 kPa in the upper 300 mm of soil. Harris (1978) and Doorenbos & Kassam (1979) recommend a 30 to 50% depletion of plant-available water from the root zone. In a previous study conducted with the cultivar Up-to-date, it was found that a 50% depletion of plant-available water from the root zone (600 mm deep) resulted in the most favourable compromise between acceptable yield, quality and water-use efficiency (Steyn, Du Plessis & Nortjé, 1992).

Water stress affects the potato plant in many ways. According to Coleman, Tai, Clayton, Howie & Pereira (1993), leaf elongation and tuber volume expansion cease when soil-water potentials are still as high as -40 to -50 kPa. Jefferies (1989) recorded a decrease in leaf growth rate when leaf water potential dropped below -280 kPa and growth ceased when it reached -1100 kPa. Water stressed crops exhibit slower and lesser canopy expansion (Jefferies, 1993; Jefferies & MacKerron, 1993) and therefore the maximum leaf area index is reduced (Van Loon 1986; MacKerron, 1989).

Water stress, furthermore, usually causes early senescence, thereby shortening the life cycle of the plants (Susnoschi & Shimshi, 1985; Van Loon, 1986). According to Spitters, Neele & Schapendonk (1988), differences in total dry matter accumulation of potato genotypes are largely explained by differences in cumulative radiation interception. It therefore seems reasonable to assume that those genotypes that maintain canopy expansion and maximum radiation interception will achieve greater dry matter production, and possibly harvestable yields, under drought conditions (Jefferies & MacKerron, 1993). The harvest index, or the fraction of assimilates partitioned to the tubers, is another important factor to be considered: Jefferies & MacKerron (1993) observed reductions in the harvest index of droughted treatments in some potato genotypes.

Since plant water status also affects physiological processes such as photosynthesis and stomatal behaviour (Van Loon, 1986), these processes have been investigated as indicators of water stress as part of this study. According to various reports, stomatal resistance is a suitable indicator of plant water status (Rutherfoord & De Jager, 1975; Dwelle, Kleinkopf & Pavek, 1981; Dwelle, 1985; Bansal & Nagarajan, 1986; Oosterhuis & Walker, 1987; Vos & Groenwold, 1989). Stomatal closure affects transpiration and photosynthetic rates, which may lead to decreased tuber yields.

The influence of water stress on the photosynthetic rates of crops, including potatoes, has been studied extensively (Munns & Pearson, 1974; Shimshi, Shalhevet & Meir, 1983; Dwelle, 1985; Van Loon, 1986; Ceulemans, Impens, Laker, Vanassche & Mottram, 1988). Reduced photosynthetic rates due to water stress have often been found (Bodlaender *et al.*, 1986; Van Loon, 1986), but marked differences in assimilation rates between genotypes (Moll, 1983) and seasons (Dwelle, Kleinkopf, Steinhorst, Pavek & Hurley, 1981) have also been reported. According to Dwelle *et al.* (1981), yield correlates poorly with photosynthetic rate and stomatal resistance, the reason being that photosynthetic rate per unit leaf area is not the sole determinant of yield. Canopy assimilation rates for the full season, as well as the partitioning of assimilates, should also be considered. According to Wilcox-Lee & Drost (1990), the partitioning of assimilates may be more important even than the actual assimilation rate in determining economic crop yields. However, since more than 90 % of the dry weight of a plant such as the potato is derived from photosynthetically fixed CO_2 (Zelitch, 1975), high photosynthetic rates are essential in order to achieve higher yields, in spite of the poor correlations sometimes recorded between short-term photosynthetic rate and yield (Dwelle, 1985). It is therefore suggested that plant breeders should strive to cross parental material with high overall photosynthetic efficiency with parents that have efficient partitioning of assimilates to the tubers.

Although single measurements of assimilation rate do not always show a correlation with tuber yield, some researchers have been able to show a correlation between the reduction in photosynthetic rate associated with water stress and drought tolerance in some genotypes. A study by Schapendonk *et al.* (1989), showed that the greatest reduction in photosynthetic rate occurred when a drought-sensitive cultivar was subjected to water stress. Sukumaran, Ezekiel & Perumal (1989), reported drought-induced reductions in assimilation rates of 32% for drought tolerant and 84% for drought susceptible genotypes.

The specific effects of water stress on yield, tuber-size distribution and tuber quality depend on the physiological stage at which the plant is exposed to the stress (Struik & Van Voorst, 1986). Water stress at almost any stage during the growing season, but especially during the tuber bulking phase (Miller & Martin, 1987b; Ojala, Stark & Kleinkopf, 1990), will result in lower tuber yield. According to Struik & Van Voorst (1986), drought reduces the number of harvestable tubers by reducing the number of tubers that grow into a certain minimum size, without affecting the number of tubers initiated. Miller & Martin (1987b) have also suggested that irrigation treatment has no effect on number of tubers and that the reduction in total yield is largely due to reduced tuber size. Haverkort, Van der Waart & Bodlaender (1990), however, have recorded a reduction in the number of stolons (and tubers) per stem as a result of early drought stress. This finding was supported by the work of MacKerron (1989), who found that the number of tubers produced per stem is influenced by the water supply in the early part of the growing season: water stress during tuber initiation phase reduces the number of potential tubers. In addition, the size distribution of tubers is usually hampered by water stress (Miller & Martin, 1987b; MacKerron & Jefferies, 1988; MacKerron, 1989). MacKerron (1989) noted that drought influences the marketable yield through two opposing effects: the reduction in total yield shifts the grade distribution downwards (a greater proportion of small tubers), while the reduction in number of tubers has a slight effect in shifting the distribution upwards.

Water stress may also have adverse effects on tuber relative density and reducing sugar content, two quality characteristics commonly affected by water supply. Tuber relative density, which gives an indication of tuber dry matter content, is usually enhanced by water stress late in the growing season (Trebejo & Midmore, 1990; Jefferies & MacKerron, 1993). Dry matter content of tubers tends to increase progressively during the growing season of the crop (Jewell & Stanley, 1989; Brown, MacKay, Bain, Grittith & Allison, 1990; Richardson, Davies & Ross, 1990b), but the pattern of increase varies greatly between crops and years (Jefferies, Heilbronn & MacKerron, 1989). The final dry matter and reducing sugar contents at harvest are influenced by cultivar, cultural practices and the environment. In some cases abnormally high sugar accumulation occurs in tubers during storage as a result of stresses to the potato plant during the last part of the growing season, such as excessively high temperatures, lack of water or high fertiliser applications late in the growing season (Sowokinos, 1990).

The dry matter content and reducing sugar content of tubers are important characteristics of tuber quality, particularly in crops intended for processing (Jefferies *et al.*, 1989). Crisping is a dehydrating process and the yield of crisps is therefore dependent on the dry matter percentage of the tubers (Logan, 1989). Tubers high in reducing sugars produce fries and crisps (dry chips) which are dark in colour due to the Maillard non-enzymatic browning reaction, involving reducing sugars and amino acids (Owings, Iritani & Nagel, 1978). Desirable colour in final products is strongly emphasized in the potato processing industry, and in the chipping industry (fries and crisps) it is absolutely critical (Orr & Janardan, 1990).

Interrupted irrigation during the growing season often leads to tuber malformations. Water stress after tuber formation can cause temporary slowing down or cessation of individual tuber growth (MacKerron, 1989). If such conditions are followed by a more favourable period, rapid renewed growth may cause tuber disorders like malformation, growth cracks and secondary growth.

CHAPTER 3

TRIAL PROCEDURES

3.1 General

The trials described in the following sections were all carried out at the ARC-Roodeplaat experimental farm north-east of Pretoria. Climatic conditions allow two growing seasons per annum for potatoes, which is typical of some subtropical climates (Levy *et al.*, 1990). In spring plantings potatoes were planted towards the end of August, when temperatures are relatively low and day lengths short. Temperatures, day length and irradiation increase as the season progresses, with maximum levels at harvesting in December. In the autumn, growth starts when temperatures are high and day length long (February), and continues under decreasing temperatures, day length and irradiation until about the end of May to early June, when plants are killed off by frost. Climatic data for the respective trial seasons are presented in Figure 3.1.

Trials started in the autumn of 1992, when the six most important potato cultivars were evaluated simultaneously. Two of the four replicates were located in each of the two rain shelters used. After the first season it was realized that the plots were too small, leading to a high level of variation in the data. It was decided to initially reduce the number of cultivars to three: the most important early- (short-) and medium-season cultivars, and a late- (long-) season cultivar which is known to be fairly drought-tolerant (Rossouw & Waghmarae, 1995). Plot size was increased from 4.5 to 5.4 m^2, resulting in a reduction in the number of replicates from four to three. There was also some concern about the small amounts of water (±7 mm) regularly received by the driest treatment, which is not typical of field situations. Two irrigation management methods, one in each of the rain shelters, were consequently evaluated during the spring planting of 1992 and autumn of 1993, using the three cultivars mentioned. The management methods are fully described in Section 3.2.

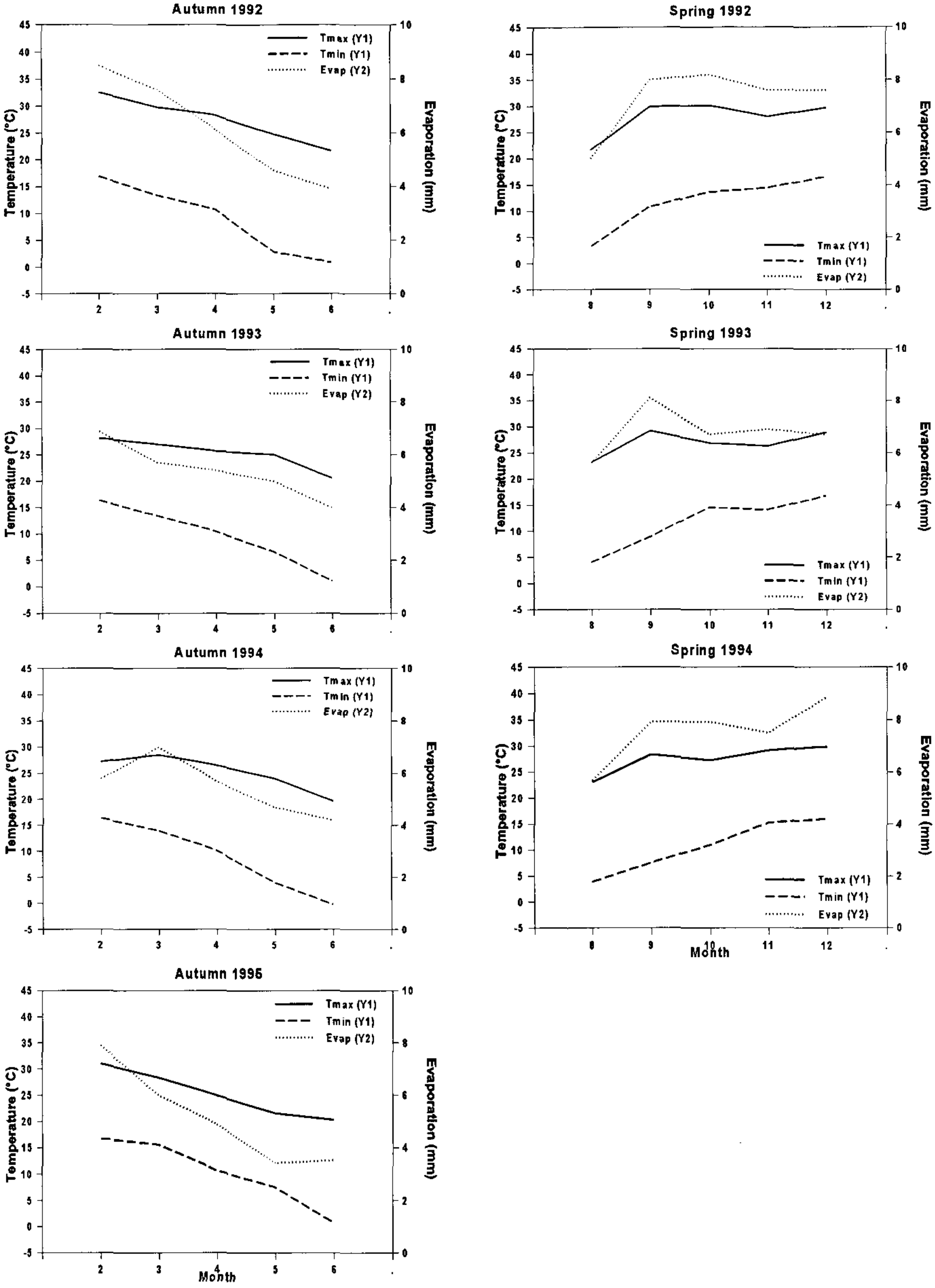


FIGURE 3.1 : Mean daily minimum and maximum temperatures, as well as average daily Class A-pan evaporation for the months of the different seasons during the trial period

In the first three plantings described above, cultivars ranging from very short to very long growing seasons (early to late cultivars) were included in the same trial. Consequently, by the time that some cultivars had senesced, others were still actively growing. This posed problems with the method of irrigation used, where cultivars could not be irrigated separately. It was therefore decided to group cultivars in more or less the same maturity class in subsequent trials. Late- to medium-late cultivars were grouped in one rain shelter, while medium to early cultivars were grouped in the second shelter. In all subsequent plantings, Late Harvest was included as a standard late cultivar and Up-to-date as a standard medium cultivar. Two other genotypes (cultivars or breeding lines) of the same maturity class were included with each of the standards. Each of the genotypes was evaluated in both a spring and an autumn planting, starting in the spring of 1993 until the autumn of 1995. Details of the genotypes included in the various trials are presented in Table 4.1.

3.2 Field screening technique for water use and drought tolerance studies

Introduction

The well-documented sensitivity of potatoes to drought (Van Loon, 1981) is a major concern in South Africa due to its low annual rainfall and poor rainfall distribution in most parts of the country (Mould & Rutherfoord, 1980). Consequently, a major objective in potato plant breeding programmes for rainfed conditions in semi-arid regions, such as South Africa, is the selection of more drought-tolerant material (Mahalakshmi, Bidinger & Rao, 1990). In the local breeding programme, selection for better adaptability to drought is aimed not only at dry-land potato production, but also at production under irrigation, as water is a limited resource also for irrigation farmers.

Evaluating the relative performance of cultivars in locations where drought is likely to occur is dependent on annual weather changes and is extremely time consuming (Mahalakshmi *et al.*, 1990). Methods have consequently been developed to induce drought stress in the more controlled environment of a glasshouse (Pennypacker *et al.*, 1990), including methods that rely on regulating the timing and amount of water given to the potted plant (Rossouw & Waghmarae, 1995) and the incorporation of an osmoticum such as polyethylene glycol (PEG) into the growth medium (Schapendonk *et al.*, 1989). Although these methods induce stress, there are potential problems with most of them. The use of osmotica like PEG and NaCl lower the soil-water potential, but may have additional adverse effects on the plant. PEG may interfere with phosphate uptake and be toxic to plants (Emmert, 1974 referred by Pennypacker *et al.,* 1990), while NaCl may cause salinity stress to the plants. The effect of drought may thus be confounded by other stresses in the plant. In pot trials, water stress usually develops rapidly due to container size. This is in contrast to the gradual development of drought in the field, which allows plants to acclimatise to the stress (Pennypacker *et al.,* 1990). Biotechnological screening methods include the search for drought-related proteins (Van der Mescht, De Ronde & Rossouw, 1992), but even these methods need to be verified by the evaluation of field performance (Rossouw & Waghmarae, 1995). From the preceding discussion, there is clearly no reliable alternative to field screening for drought tolerance in plants at this stage.

The line-source sprinkler irrigation technique (Hanks, Keller, Rasmussen & Wilson, 1976) has recently been used extensively in water-use and drought-screening trials (Bresler, Dagan & Hanks, 1982; Barragan & Recasens, 1988; Mahalakshmi *et al.*, 1990; Fernandez, 1991; Singh, Rao & Williams, 1991). The system gives rise to a continuously variable soil-water regime along a gradient from excess water to no water added. It also has the advantage of minimizing the experimental area, since there is no need for border rows because of the small incremental change in water applied between adjacent treatments (Mahalakshmi *et al.*, 1990). The experimental design is similar to a strip-plot or strip-block design, except that irrigation levels are systematically arranged without randomization (Fernandez, 1991). Other factors, such as genotypes or fertility levels, can be studied by placing treatment variables in strips at right angles to the irrigation treatment (Hanks, Sisson, Hurst & Hubbard, 1980). Since water treatments are not randomized there is no valid univariate statistical test available to test for the main effects of water (Fernandez, 1991, Hanks *et al.*, 1980). The irrigation effects are, however, usually large and, according to Hanks *et al.* (1980), there should be no need to assign a probability level to their significance. Some statistical techniques have since been developed to overcome the problem (Bresler *et al.*, 1982; Fernandez, 1991) and the line-source technique is widely used today in irrigation trials for many crops.

In areas where the rainy season coincides with the growing season of the crop, rains often interfere with water-stress treatments in the field (Fletcher & Maurer, 1966). Automated rain shelters have consequently been used to eliminate the interference of rain with water treatments (Upchurch, Ritchie & Foale, 1983; Kvien & Branch, 1988; Jefferies, 1993). Rain shelters usually have moveable roof structures on elevated rails or are building-like structures that move on surface-level rails (Kvien & Branch, 1988). Due to the limited space covered by rain shelters, as well as the fact that the rain shelters used in the present study moved on elevated rails, the conventional line-source system could not be used. The use of rain shelters was therefore combined with a modified version of the line-source irrigation system to evaluate water use and drought tolerance of potato genotypes.

Rain shelters and Irrigation systems

The trials were conducted at Roodeplaat near Pretoria during the period 1992 to 1995. Each of the two rain shelters covered an area of 280 m^2 (24 x 11.7 m). The roof structure of the shelters consisted of a steel construction, similar to that used for commercially available greenhouses. Polyethylene sheeting was used to cover the roof and sides of the shelters. The shelters were fully automated and driven by 380 V three-phase motors. A drop of rain onto a small sensor activated the motors to cover the trial. Once the sensor was dry (after a shower), the shelter automatically moved to the open position. This restricted the time the plants were covered. Limit switches on either end of the rails prevented the shelter from running off the rails. A complete description of the construction and operation of the shelters is given by Nortjé (1988).

The line-source principle (Hanks *et al.*, 1976) was used as a departure point and adapted for use with rain shelters to allow the inclusion of water levels and cultivars as treatments. A travelling boom, mounted on an A-frame was attached to the inside roof structure of each shelter. The A-frame had four wheels that moved in tracks along the length of the shelter and was driven by a 220V electric motor. Limit switches on both sides of the shelter ensured the continuous shuttling of the boom along the shelter, as long as the power was switched on. Water was supplied to the boom by means of a trailing hose that moved along with the boom. The same applied to the electricity supply to the electric drive motor. Flat fan nozzles were mounted onto the boom (constructed of 25mm galvanised pipe) at a spacing of 750 mm. This spacing allowed the spread of 15 nozzles across the width of the boom. Five water-treatment strips of three rows each were achieved by the use of Tee-jet (R) nozzles with different discharge rates. This resulted in a step-wise change in the amount of irrigation, instead of the gradual decline associated with the conventional line-source. The nozzles had a 50 ° spray angle to prevent overlapping with adjacent rows and plots. PVC plastic sheeting (0.4 mm in thickness) was installed to a soil depth of 1 m between water-treatment strips to prevent lateral water movement. It is assumed that the adjacent water treatments had no effect on each other.

Whenever irrigation was necessary, the shelter was drawn over the crop, the water hose and power supply connected and switched on. Canvas strips attached to the side panels of the shelter were let down before irrigation to limit water drift caused by wind. Irrigation water was supplied from a 10 000-litre reservoir with the aid of a booster pump. A constant operating pressure of 120 kPa was ensured by the use of pressure regulators. At constant pressure the fraction of the total amount of water which was applied by a nozzle of specific size remained the same. It was therefore possible to calculate the exact amount of water applied to each treatment, as the discharge rate of each nozzle at 120 kPa was known.

The accuracy of water application could not be checked by catch cans or rain gauges as is usually done (Miller & Martin, 1987b; Trebejo & Midmore, 1990), because of the uneven distribution of water within the same treatment. The Tee-jet nozzles used are designed to overlap 30% in their spray pattern in order to ensure even water application. At the spacing of 750 mm and 50° spray angle, the rate of application was therefore uneven, leading to dry (between the rows) and wet strips (on the rows) (Figure 3.2). The boom was therefore occasionally checked during each season by collecting the discharge of each nozzle in plastic containers during a twenty-second period. This was done while the boom stood stationary in the open position. The results of some checks are shown in Table 3.1 as an example.

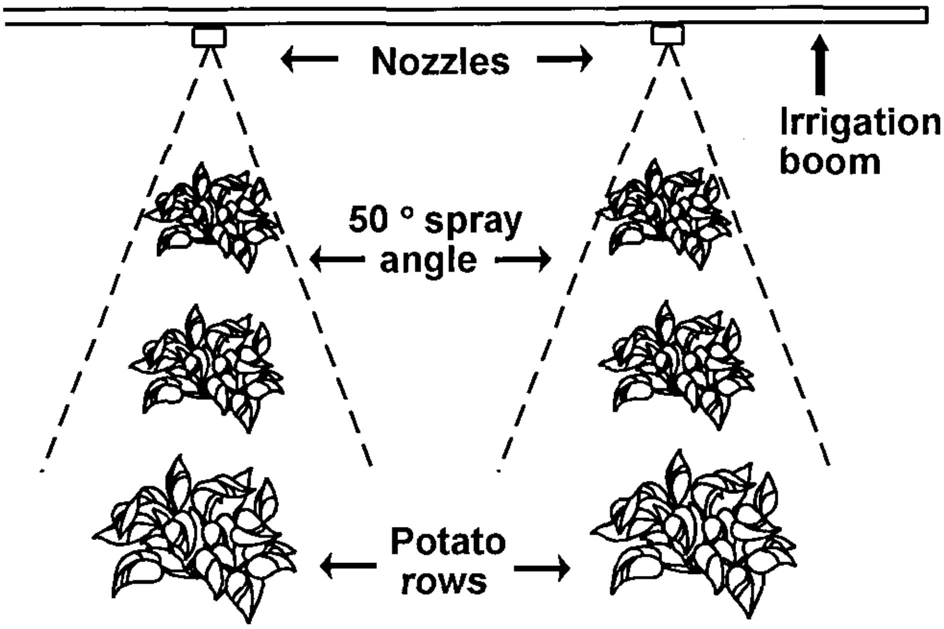


FIGURE 3.2: **Schematical presentation of the spray pattern of irrigation nozzles to prevent overlapping with adjacent plots**

The amount of water discharged by the nozzles of each treatment is expressed as a fraction of the amount applied to the wettest treatment (W1). The total amount of water applied to each treatment is therefore easily calculated.

The irrigation scheduling of the W1 treatment was based on neutron-probe measurements of the soil-water content. A maximum depletion of 20 % of the water held at field capacity (in the zone of active roots at that stage) was allowed for this treatment. At full canopy, irrigation scheduling was based on a rooting depth of 600 mm. For the specific soil it resulted in W1 being irrigated whenever about 25 mm of soil water was depleted. For the 1993 planting, for example, treatments W2, W3, W4 and W5 of rain shelter # 1 received 20.5 mm, 16.25 mm, 11.5 mm and 7.5 mm, respectively, every time W1 was irrigated 25mm (Table 3.1). In the 1992 spring and 1993 autumn plantings two irrigation management methods, one in each of the rain shelters, were evaluated. The irrigation scheduling of rain shelter # 1 was carried out

Table 3.1 : Discharge rates of different nozzles used in five water treatments. Amounts in *mℓ water collected per 20-second period.* Standard error of means in parenthesis

Date mm-yy	Rain shelter no.	Water treatment									Total mℓ
		W1	W2		W3		W4		W5		
		mℓ	mℓ	%	mℓ	%	mℓ	%	mℓ	%	
10-93	1	775 (4.9)	633 (7.1)	81.7	428 (3.5)	55.2	347 (3.8)	44.7	215 (1.1)	27.8	2398
11-94	1	666 (6.9)	586 (5.6)	88.5	411 (2.6)	61.7	334 (3.6)	50.1	210 (4.8)	31.5	2207
04-95	1	743 (2.4)	616 (2.6)	83.0	417 (1.5)	56.1	341 (1.8)	46.0	210 (1.3)	28.3	2327
10-93	2	751 (6.02)	626 (5.2)	83.2	432 (3.6)	57.5	351 (0.7)	46.7	212 (1.8)	28.2	2371
11-94	2	729 (9.2)	604 (6.5)	82.9	427 (6.3)	58.6	341 (3.8)	46.8	201 (5.2)	27.6	2302
4-95	2	739 (2.0)	607 (1.4)	82.2	416 (1.7)	56.3	340 (1.1)	46.0	210 (2.2)	28.4	2312

according to the method described above. In rain shelter # 2, the drier treatments were, however, not irrigated simultaneously with W1. The fractions of water they were suppose to receive were accumulated, so that all treatments were irrigated a minimum of 20mm per application. The purpose of the investigation was to determine whether genotype performance is influenced by the irrigation amount per application, as there was some concern about the small amounts of water (±7mm) regularly applied to the driest treatment (W5) of rain shelter # 1.

The bronze nozzles were replaced annually as it was observed that wear and tear started to change the discharge rates after some time. Special attention was paid to ensure that irrigation water was sufficiently filtered and free of materials that could cause nozzle clogging. Nozzles were also removed and cleaned regularly to prevent furring of the orifices. Actual water use and yield data obtained from trials conducted according to the described technique are presented in Chapters 4 and 7.

CHAPTER 4

THE EFFECTS OF DIFFERENT WATER REGIMES ON TUBER YIELD AND SIZE DISTRIBUTION

4.1 Introduction

The detrimental effects of drought on potato tuber yield are well known (Struik & Van Voorst, 1986; Miller & Martin, 1987b; Levy *et al.*, 1990; Spitters & Schapendonk, 1990). In general, total tuber yield is reduced by water stress at almost any stage during the growing season of a potato crop (Mould & Rutherfoord, 1980), but especially during the tuber bulking phase (Miller & Martin, 1987b; Ojala, Stark & Kleinkopf, 1990).

Apart from lower total tuber yield, water stress may also adversely affect the tuber-size distribution (Struik & Van Voorst, 1986; Miller & Martin, 1990). Miller & Martin (1987b) have suggested that the reduction in total yield as a result of water stress is largely due to reduced tuber size. Droughts generally cause a downward shift in tuber-size distribution. According to Struik & Van Voorst (1986), drought reduces the number of harvestable tubers by reducing the number of tubers that grow beyond a certain minimum size. The consequence of drought is, therefore, that a smaller fraction of the total yield reaches the minimum size required for a specific size class (MacKerron & Jefferies, 1988). This may not be desirable as most markets have specific preferences regarding the optimum tuber size required.

Little is known about the response of South African potato cultivars to water stress. From an earlier study conducted with the cultivar BP1, Mould & Rutherfoord (1980) concluded that physiological disorders and poor processing quality result from early water stress, while tuber yield is severely hampered by stress during the latter half of the bulking period. Jefferies & MacKerron (1987) reported differences between cultivars in reductions of yield because of drought. They also showed that drought affects the size distribution of cultivars differently.

Changes in tuber-size distribution may have significant consequences for the producer, as his product may not satisfy the needs of the consumer, be it for processing or the fresh market. In this chapter the result of different water regimes on total yield and tuber-size distribution of some commercial potato cultivars and breeding lines is investigated.

4.2 Materials and methods

Field experiments were conducted on a sandy loam (Oakleaf soil form) at the ARC-Roodeplaat Vegetable and Ornamental Plant Institute near Pretoria during the period 1992 to 1995. The soil has an average clay content of 15% in the upper 600 mm of the profile, is well drained and has a volumetric field capacity of about 25%.

The genotypes evaluated during the different plantings are listed in Table 4.1. Seven trials were carried out during the test period. An irrigation boom (Chapter 3, section 3.2) was used to impose five different water treatments. The control treatment (W1) was irrigated when 20% of the water held in the soil at field capacity was withdrawn from the root zone. The other treatments (W1 - W5) were irrigated simultaneously, and received approximately 82%, 62%, 46% and 30% respectively of the amount applied to W1 (see Table 3.1 for specific fractions applicable to the different plantings). Soil-water content was determined three times per week to a depth of 1200 mm by neutron probe (CPN 503). Automatic rain shelters prevented the interference of rain with irrigation treatments. Details of the trial layout, as well as the experimental design, are presented in Chapter 3, sections 3.1 and 3.2.

The same rain shelter site was used during the entire trial period, but the area planted alternated between the two positions covered by each rain shelter. The part that was planted during the spring planting was the stationary position of the rain shelter in the autumn, and *vice versa.* The soil was fumigated with methyl bromide at a rate of 60 g m^{-2} before each planting to limit the possible adverse effects of successive potato crops. A rototiller was used for seedbed preparation, whereafter furrows were made using a two-wheel tractor and potato

TABLE 4.1 List of genotypes included in water use trials conducted in spring and autumn plantings over four years.

Year	Planting	Rain shelter #1		Rain shelter #2	
		Genotype name	Maturity class	Genotype name	Maturity class
1992	Autumn	Vanderplank Buffelspoort Up-to-date BP1 Kimberley Choice Late Harvest	Early Early Medium Medium Late Late	Vanderplank Buffelspoort Up-to-date BP1 Kimberley Choice Late Harvest	Early Early Medium Medium Late Late
1992 and 1993	Spring Autumn	Vanderplank Up-to-date Late Harvest	Early Medium Late	Vanderplank Up-to-date Late Harvest	Early Medium Late
1993 and 1994	Spring Autumn	Late Harvest Hoëvelder Mnandi	Late Late Medium-late	Up-to-date 82-252-5 83-252-1	Medium Medium Medium-early
1994 and 1995	Spring Autumn	Late Harvest 81-163-40 83-363-67	Late Medium-late Medium-late	Up-to-date Mondial 84-304-4	Medium Medium Medium

ridger. Fertiliser and insecticide (aldicarb) were banded in the furrows at recommended rates An example of a typical fertiliser application is shown in Table B12 of the Appendix.

The potato seed pieces were planted by hand at a row spacing of 750 mm and 300 mm within the row. Weeds were controlled manually by hoeing. The potatoes were ridged (hilled) 3 to 4 weeks after emergence, when plants were about 300 mm in height. Run-off was prevented during the season by small dams across the furrows at either edge of each plot. All plots were initially irrigated uniformly, using another set of nozzles, to ensure good emergence and establishment of the crop. Irrigation treatments were initiated 3 to 4 weeks after emergence and continued until the date of senescence or haulm destruction, whereafter the dry treatments were irrigated 10 - 15 mm to ease the harvesting process.

Tubers were lifted by hand two weeks after haulm killing to ensure proper skin set, graded into different sizes and weighed. Grading of tubers was done according to the categories that were the commercial standards at the start of the trial, namely:

1. "Chats" (not marketable)	<50 g
2. Small	50 - 100 g
3. Medium	100 - 250 g
4. Large	>250 g

The marketable yield used in the analysis of data consisted of the small, medium and large tubers. The yield of chats was generally very low and excluded from the data. Tuber quality aspects such as secondary growth, mechanical damage and tuber diseases were not taken into consideration in the total yield calculations. Generally almost no diseases or mechanical damage occurred for any of the trials. Secondary growth was, however, common for some genotypes in the hot spring plantings. These deviations were more pronounced for the heat sensitive genotypes, such as Up-to-date.

The format of the trial was changed after the first autumn planting (see Section 3.1 for details). The first autumn trial was considered a pilot trial and its results were analysed separately, using the AMMI (additive main effects and multiplicative interaction) model as described by Yau (1995). For the remaining years the marketable yields for the same plantings (either spring or autumn) were combined and the AMMI model was used for data analysis. The model is able to combine and analyse data from trials in different environments, even if all the entries (genotypes) are not present in all trials. This is a suitable method to compare environment X genotype effects over seasons (Yau, 1995). The 1992 spring and 1993 autumn trials in rain shelter #2 had a different irrigation management method (Chapter 3). The data were, however, not excluded from the data set, as the relative performance of the cultivars involved did not seem to change as a consequence of management method. The data of the spring and autumn plantings were analysed separately due to expected different reactions to water treatments in the two plantings. This trend was reported by Lemaga & Caesar (1990), who worked in similar conditions in a subtropical climate. Such differences in yield can be attributed to the differences in temperature, day length and irradiation levels between spring and autumn plantings (see Section 3.1). The same standard cultivars were not used in the two rain shelters because of differences in maturity classes, and could therefore not be compared directly. In the two plantings mentioned above, there were different maturity classes in the same rain shelter, but for the purpose of data analysis, the genotypes in rain shelter #1 were considered late cultivars, and those in rain shelter #2 medium cultivars.

4.3 Results and discussion

4.3.1 Tuber yield

AUTUMN 1992 (PILOT TRIAL)

Since the relationship between water applied and water used was linear, the fractions of water applied to the different water regimes are plotted in the water-yield curves. Figure 4.1 display the absence of genotype X water interaction for this trial (summary of the AMMI analysis of variance in Table B1 of the Appendix for a). The genotypes all follow the same declining trend in yield with less water used.

The mean yield of each genotype (over water treatments) was plotted against their corresponding "interaction of principal components analysis" (IPCA1) scores (Figure 4.2). The magnitude of the IPCA1 scores indicate the degree of interaction between genotypes and different levels of water. A large positive or negative score is an indication that the genotype shows strong interaction with different levels of water. A genotype might, for instance, perform well at a sufficient level of water, but be poorly adapted to lower levels of water, and *vice versa*. A small score, on the other hand, indicates that the genotype has a more stable response to a range of water levels. Genotypes with similar response to water are grouped together according to a hierarchical clustering of AMMI estimates over water levels. The average yields for water treatments (over genotypes) were also plotted against their corresponding IPCA1 scores on the same biplot. Grouping of genotypes and water treatments on the same side of the zero score line indicates that those genotypes will respond well to that

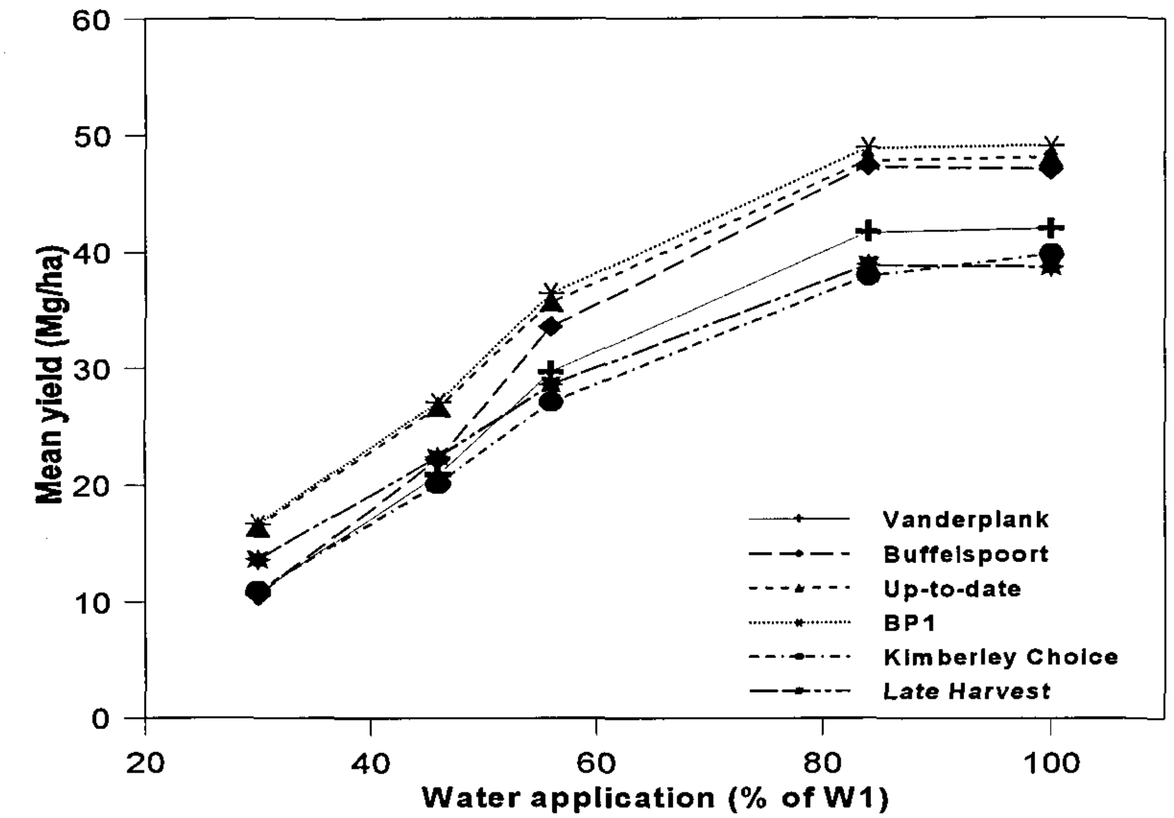


FIGURE 4.1 : Water-yield curves of six potato genotypes exposed to five levels of water during the autumn 1992 season (pilot trial)

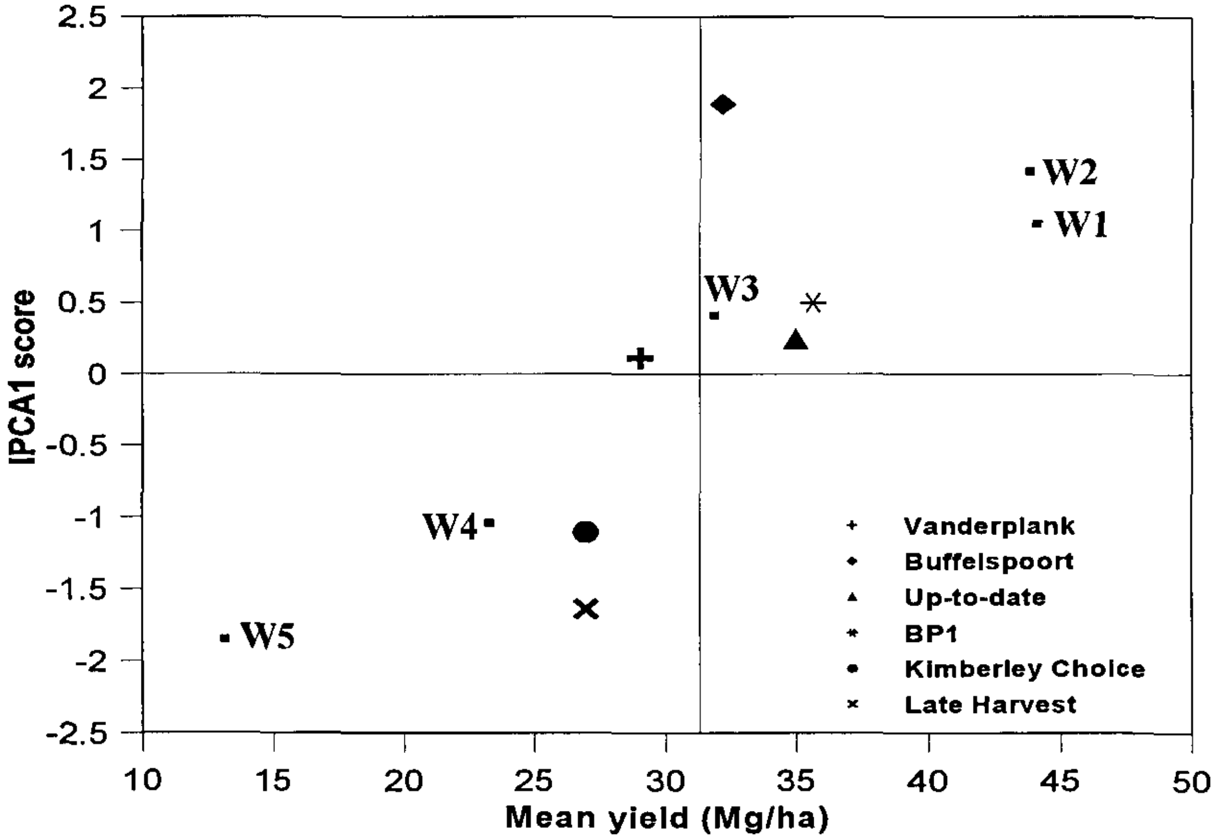


FIGURE 4.2 : AMMI IPCA1 scores and mean tuber yield of six potato genotypes as influenced by five levels of water during the autumn 1992 season (pilot trial)

water treatment. The further the points are apart, the greater the contrast between the response of a specific genotype and water treatment. It is therefore possible to get a quick visual impression of the expected performance of genotypes at certain levels of water.

Water levels W1 and W2 grouped together and contrasted with the other water treatments, indicating that the responses to both were very similar (Figure 4.2). The genotypes Buffelspoort, Kimberley Choice and Late Harvest showed the greatest interaction with levels of water. The Buffelspoort score contrasted strongly with the dry treatment scores, indicating that Buffelspoort performs best at the wetter treatments. The scores of the two late cultivars, Late Harvest and Kimberley Choice, on the other hand, contrasted with the wet treatment scores, indicating that they performed worse than the other genotypes with ample supply of water. Genotypic differences in average yield were small and all the genotypes grouped around the average yield of 32.3 Mg ha^{-1}. Late Harvest and Kimberley Choice, the two longer growers, had the lowest average yields, while the medium cultivars Up-to-date and BP1 had the highest yields.

SPRING 1992 TO AUTUMN 1995 PLANTINGS

Some variation in the marketable yield of the standard cultivars (Late Harvest and Up-to-date) was observed over years, especially in the autumn plantings (see Tables B2 and B3 of the Appendix and the graphical presentation of actual yield and yield components in Figures 4.11 to 4.14, section 4.3.2). It was therefore clear that the physical yields of genotypes in different years could not be compared. To enable comparison of genotypes over years, the marketable yield of genotypes was expressed relative to that of the standard cultivar in the same trial. In the case of the medium-late and late genotypes, yield was expressed relative to that of Late Harvest, while Up-to-date was the standard for comparison of the medium and early genotypes.

The correctness of certain assumptions were necessary to ensure valid comparisons of the relative yield of genotypes over years. It was firstly assumed that the yield of the standard cultivars was typical ("normal") in all the trials. Secondly, it was assumed that the physiological age of seed tubers, which may have a considerable effect on the performance of progeny plants (Caldiz, 1991; Pieterse, 1994), was optimal in all trials. Care was taken to ensure that all seed tubers were at optimal physiological age when planted. Problems were, however, encountered in one planting, as discussed in Section 4.3.2. A further assumption was that the yield of the genotypes would remain the same relative to that of the standards over all the years for the same planting (spring or autumn); external factors that might have differential effects on different genotypes were thus assumed to be absent. If they were present, the ranking of cultivars might have changed as a consequence.

No abnormalities in growth were observed, except for one case in the 1994 spring planting, when the genotype 84-304-4 died off early because of *Erwinia* spp. infection. Yields of the standards also remained relatively stable for the same planting (spring or autumn) (Figures 4.11 to 4.14), except for the autumn 1995 planting, when the yields were generally low (presumably due to lower levels of solar radiation), suggesting that their growth could be assumed to have been optimal in all the trials.

Late genotypes The mean relative yields of genotypes (over water treatments) were plotted against their corresponding IPCA1 scores. This was done separately for the spring and autumn plantings (Figures 4.3 and 4.5). For all the trials since the 1992 spring planting the magnitude of the IPCA1 score indicates the interaction of a genotype with water regimes, relative to that of the standard cultivar. A high score indicates that the genotype reacted differently to the irrigation treatments, compared to the standard cultivar. Summaries of the AMMI ANOVA's are presented in Tables B4 and B5 of the Appendix.

In the spring plantings, Hoëvelder and 83-363-67 were the most stable genotypes, and both had higher average yields than Late Harvest (Figure 4.3). They performed best at the wet to intermediate water treatments (W1 to W3). Mnandi had the highest overall yield, but the biggest interaction with water levels. The average yields of Vanderplank, Up-to-date and 81-163-40 were almost the same, and all lower than that of Late Harvest. They all showed strong interaction with water.

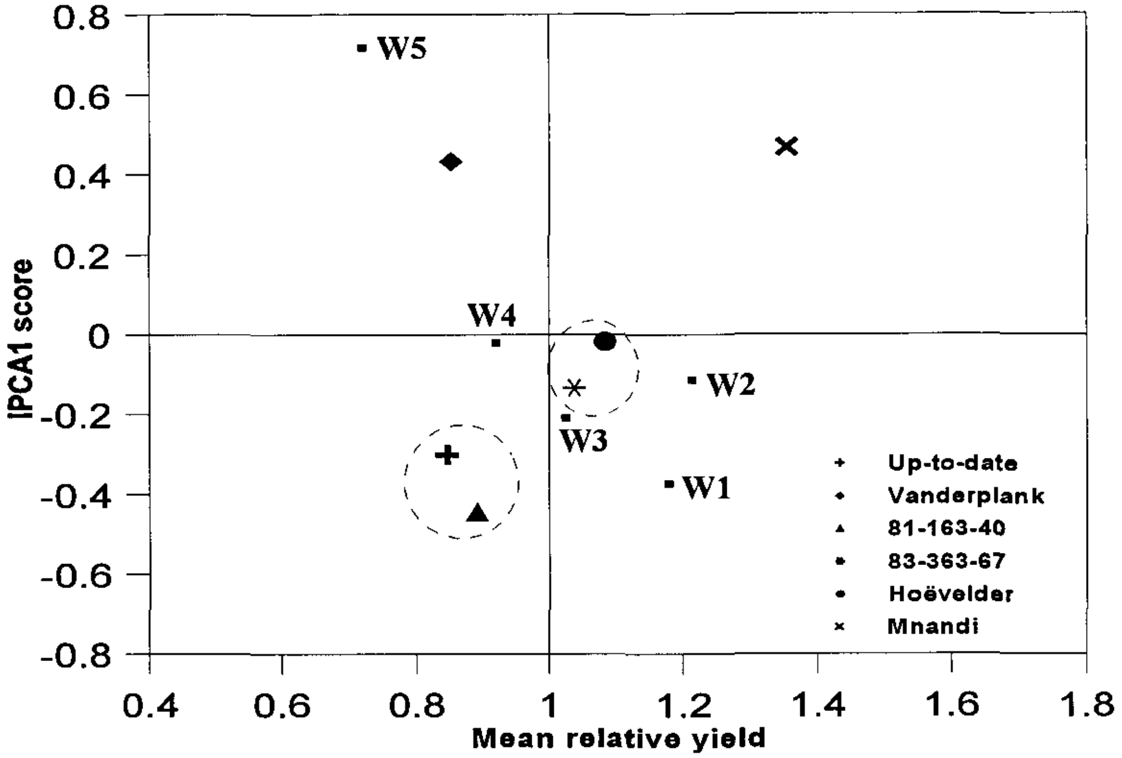


FIGURE 4.3 : AMMI IPCA1 scores and average relative tuber yields (relative to Late Harvest) of six late potato genotypes as influenced by five levels of water during the 1992 to 1994 spring seasons

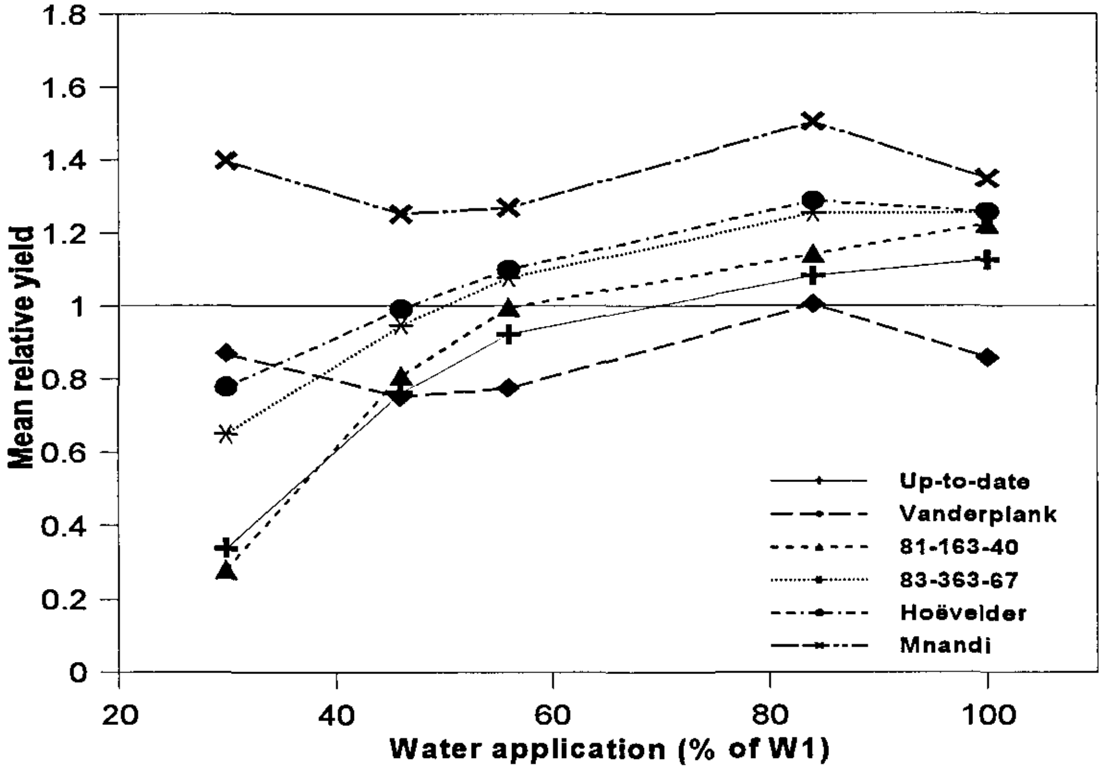


FIGURE 4.4 : Relative water-yield curves (to Late Harvest) of six late potato genotypes exposed to five levels of water stress during the 1992 to 1994 spring seasons

TABLE 4.2: AMMI preferential ranking of genotypes compared with Late Harvest as a standard according to their marketable yields at different water treatments in spring plantings

Rank no.	Water treatment				
	W1	W2	W3	W4	W5
1	Mnandi	Mnandi	Mnandi	Mnandi	Mnandi
2	Hoëvelder	Hoëvelder	Hoëvelder	Late Harvest	Late Harvest
3	83-363-67	83-363-67	83-363-67	Hoëvelder	Vanderplank
4	81-163-40	81-163-40	Late Harvest	83-363-67	Hoëvelder
5	Up-to-date	Up-to-date	81-163-40	81-163-40	83-363-67
6	Late Harvest	Vanderplank	Up-to-date	Up-to-date	Up-to-date
7	Vanderplank	Late Harvest	Vanderplank	Vanderplank	81-163-40

The AMMI preferential ranking of genotypes according to their performance at the different water levels is shown in Table 4.2. It is clear that there is almost no change in ranking between water levels W1 and W2, the reason probably being that for the W2 treatment, the soil profile could supply the portion of water usage not supplied by irrigation. When water is reduced to the level of W3, but especially at W4 and W5, the ranking of Late Harvest and Vanderplank improved from the last two positions to the second and third position, respectively. Due to its high yield potential, Mnandi remained in the first position throughout water treatments, in spite of its high interaction with water. Up-to-date, 81-163-40 and 83-363-67 moved down to the last three positions at the driest treatment (W5).

These rankings can also be represented graphically to illustrate the change in relative yields over water treatments (Figure 4.4). This may be seen as the "relative production function" of genotypes over water treatments. The response of genotypes which have relative production curves parallel to those of the standard, is similar to that of the standard. According to Figure 4.4, the response of both Mnandi and Vanderplank is similar to the response of Late Harvest, with the yield of Mnandi consistently higher and Vanderplank consistently lower than that of Late Harvest. The level of water does therefore not influence the selection of these two genotypes.

The other genotypes (Up-to-date, 81-163-40, 83-363-67 and Hoëvelder) showed a decline in relative yield with lower water use. They yielded better than Late Harvest at the wet treatments, but performed worse than Late Harvest when stressed. Of the latter four genotypes, Hoëvelder consistently had the highest yield and Up-to-date and 81-163-40 the lowest. The selection of these genotypes by the producer is therefore largely influenced by availability of water in spring plantings. When supply of water is ample, all genotypes except Vanderplank will produce higher yields than Late Harvest. When severely stressed, only Mnandi produces higher yields than Late Harvest. Vanderplank consistently had lower yields than Late Harvest, but remained stable, relative to Late Harvest. The lower yield of Vanderplank is partly attributable to it being an early cultivar, commonly associated with a lower yield potential (Levy *et al.*, 1990).

In autumn the main effects (genotypes and water levels) were significant, but the interaction between genotype and water level was not. Genotypes reacted similarly to levels of water and average yield declined with less water used (Figure 4.12). The close grouping of the mean relative yields at the different water treatments (W1 - W5 on the AMMI biplot) around the Late Harvest mean (relative yield of one) is striking (Figure 4.5). This indicates that at any of the water treatments the mean yields of the other genotypes did not change relative to that of Late Harvest, and were almost the same. The mean yield (over water treatments) was highest for 81-163-40, followed by Mnandi. Hoëvelder was the only genotype that showed considerable interaction with levels of water. The average yields of Hoëvelder, Up-to-date and 83-363-67 were lower, but close to those of Late Harvest, while Vanderplank had markedly lower yields on average. The stable relative yields of genotypes over water treatments were confirmed by their relative production functions (Figure 4.6), which followed the same tendency as Late Harvest.

Medium to early genotypes In the spring plantings only the main effect of water was significant, although genotypes showed different responses to water (Figure 4.8). Although trends were evident, the high coefficient of variance (CV = 35%) probably accounted for the interaction not being significant (summary of ANOVA presented in Table B6 of the Appendix).

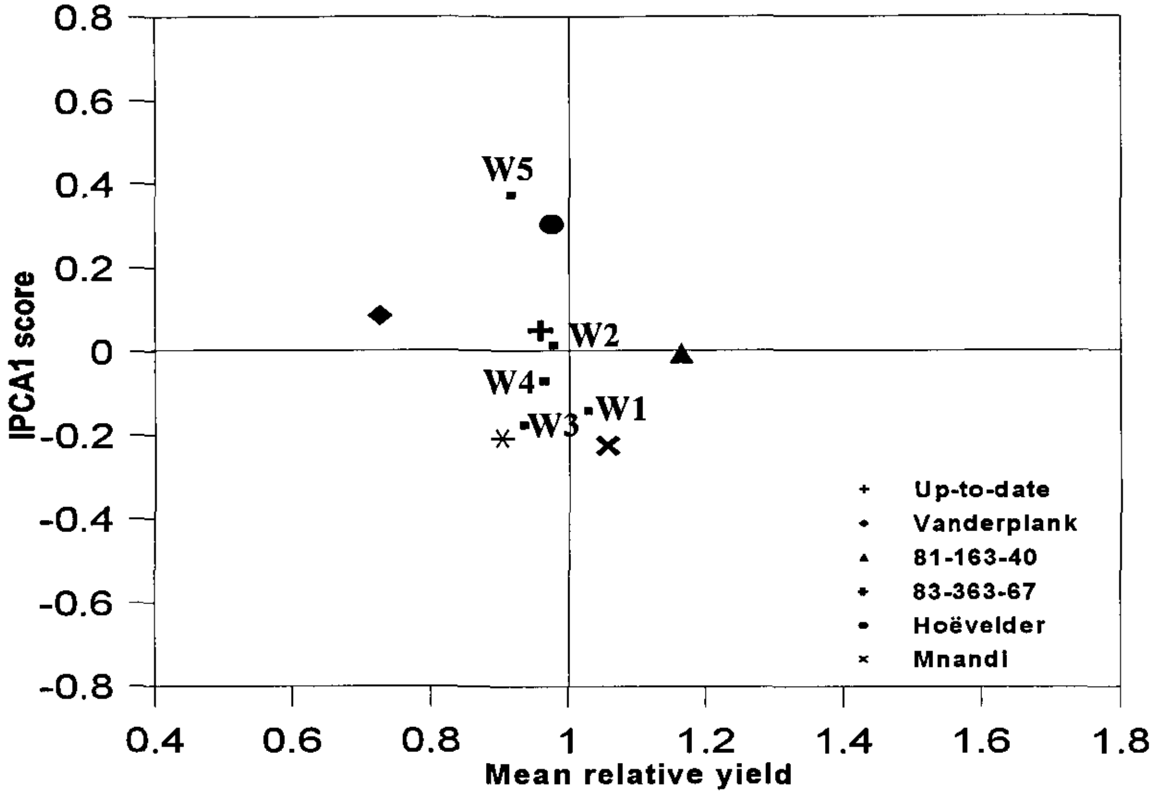


FIGURE 4.5 : AMMI IPCA1 scores and average relative tuber yields (relative to Late Harvest) of six late potato genotypes as influenced by five levels of water during the 1993 to 1995 autumn seasons

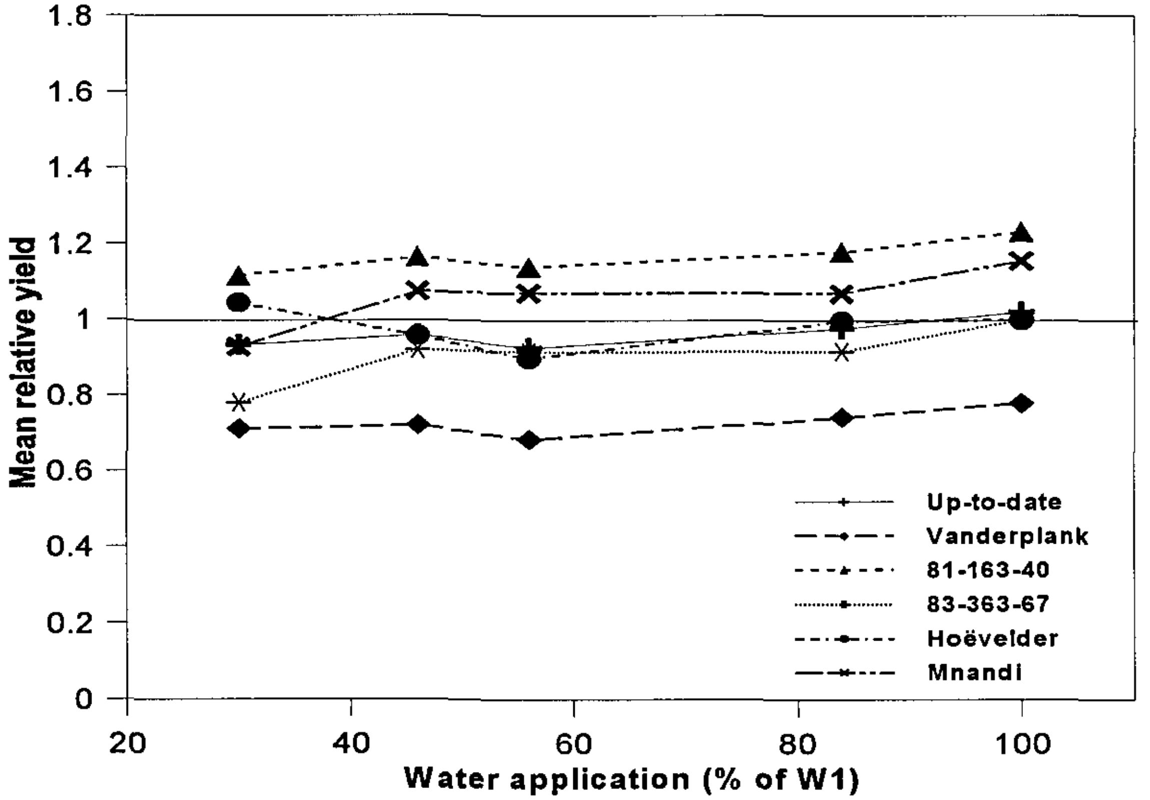


FIGURE 4.6 : Relative (relative to Late Harvest) water-yield curves of six late potato genotypes exposed to five levels of water stress during the 1993 to 1995 autumn seasons

The relative yield at W4 and W5 contrasted strongly with the yields at the wetter treatments (W1 to W3), which grouped closely together (Figure 4.7). For the wetter treatments (W1-W3) the mean yields of the other genotypes were on average lower than those of Up-to-date (< 1), while their yields were higher than those of Up-to-date at the drier treatments (W4 and W5). At W5 the yields of the other genotypes were on average almost 1.8 times those of Up-to-date. Although not statistically significant, the performance of 82-252-5 and 83-252-1 improved substantially, relative to Up-to-date, in the drier treatments (Figure 4.8). The genotypes 82-252-5 and 83-252-1 had the highest average yields, while Vanderplank and 84-304-4 had the lowest. The latter genotype (84-304-4), however, died off early because of *Erwinia* infection, and no conclusions should be drawn from its performance.

The preferential ranking of genotypes was dependent on water treatments (Table 4.3). At the wetter treatments (W1-W3) there was virtually no change in the ranking and Up-to-date outperformed all the other genotypes, with the exception of Mondial which produced similar yields. At the drier treatments (W4-W5) the other genotypes yielded as well as or better than Up-to-date. Especially the genotypes 82-252-5 and 83-252-1 performed exceptionally well at the dry treatments.

TABLE 4.3: AMMI preferential ranking of genotypes compared with Up-to-date as a standard according to their marketable yields at different water treatments in spring plantings

Rank no.	Water treatment				
	W1	W2	W3	W4	W5
1	Up-to-date	Mondial	Mondial	83-252-1	83-252-1
2	Mondial	Up-to-date	Up-to-date	82-252-5	82-252-5
3	83-252-1	Late Harvest	Late Harvest	Vanderplank	Vanderplank
4	Late Harvest	83-252-1	83-252-1	Up-to-date	84-304-4
5	82-252-5	82-252-5	82-252-5	Late Harvest	Late Harvest
6	Vanderplank	84-304-4	84-304-4	84-304-4	Mondial
7	84-304-4	Vanderplank	Vanderplank	Mondial	Up-to-date

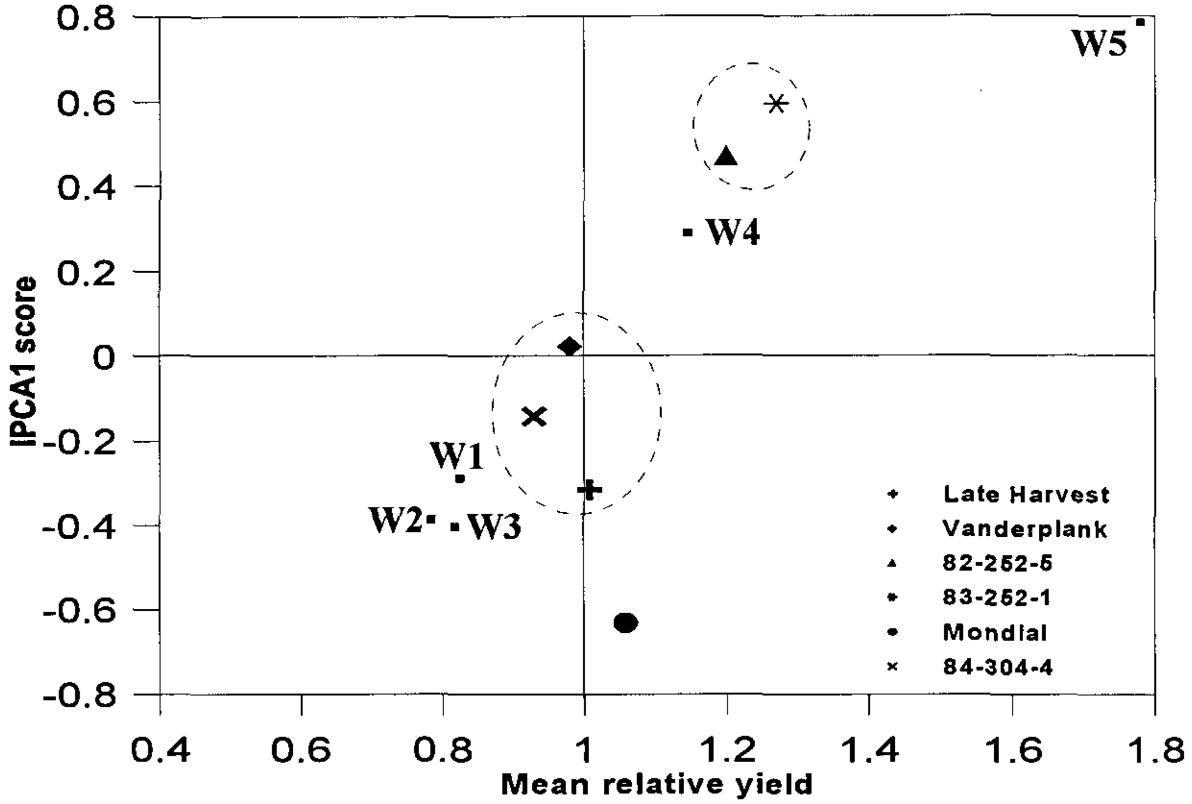


FIGURE 4.7 : AMMI IPCA1 scores and average relative tuber yields (relative to Up-to-date) of six medium potato genotypes as influenced by five levels of water during the 1992 to 1994 spring seasons

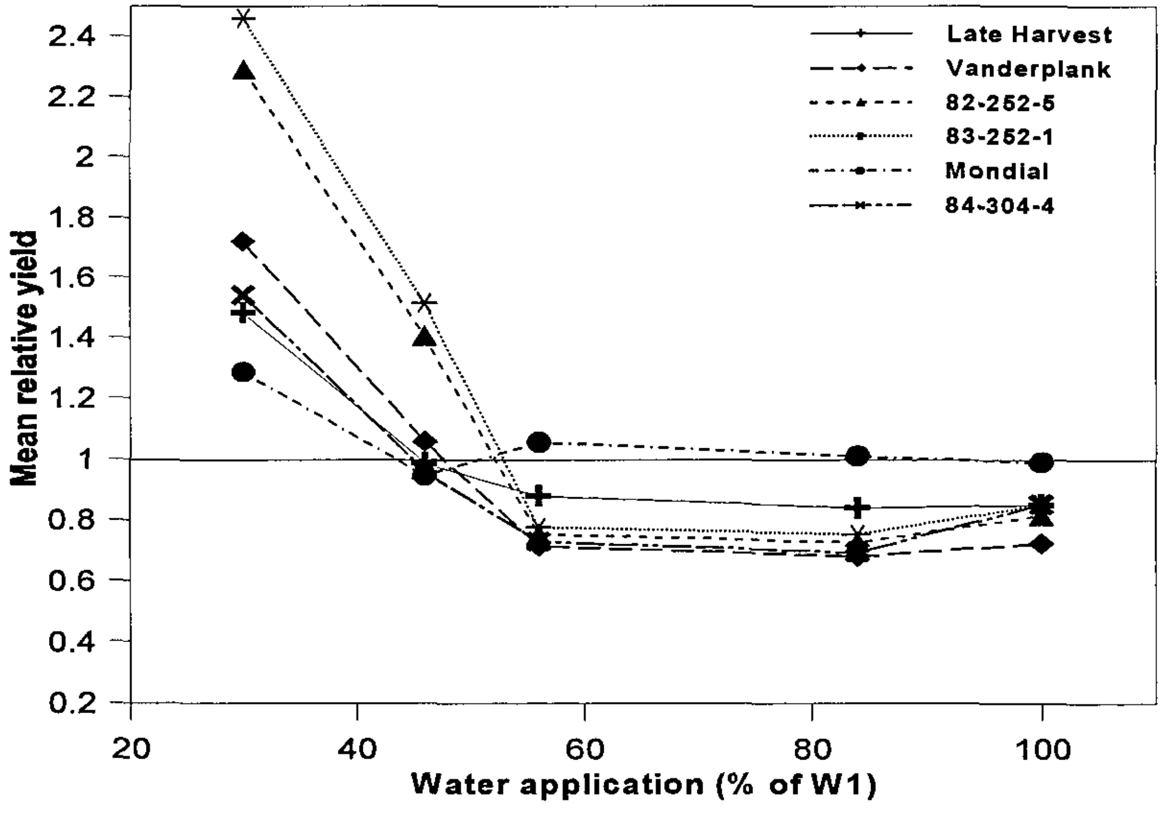


FIGURE 4.8 : Relative water-yield curves (relative to Up-to-date) of six medium potato genotypes exposed to five levels of water stress during the 1992 to 1994 spring seasons

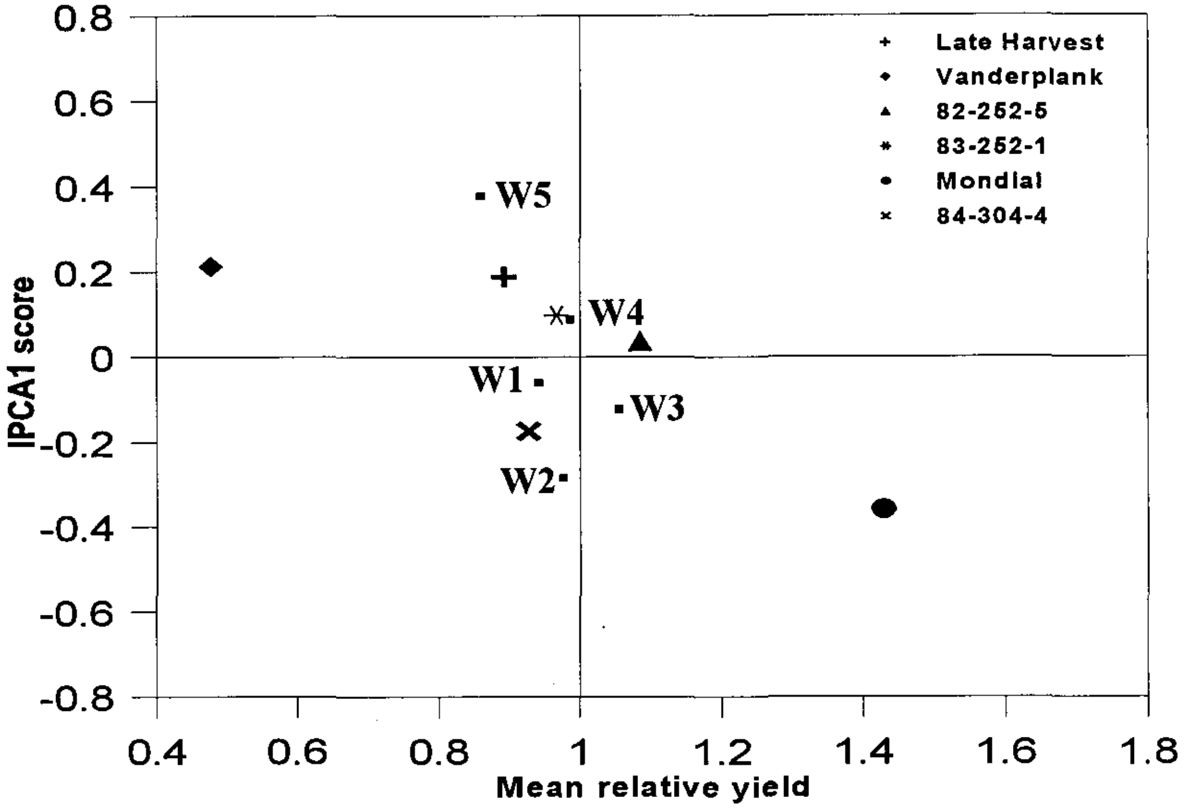


FIGURE 4.9 : AMMI IPCA1 scores and average relative tuber yields (relative to Up-to-date) of six medium potato genotypes as influenced by five levels of water during the 1993 to 1995 autumn seasons

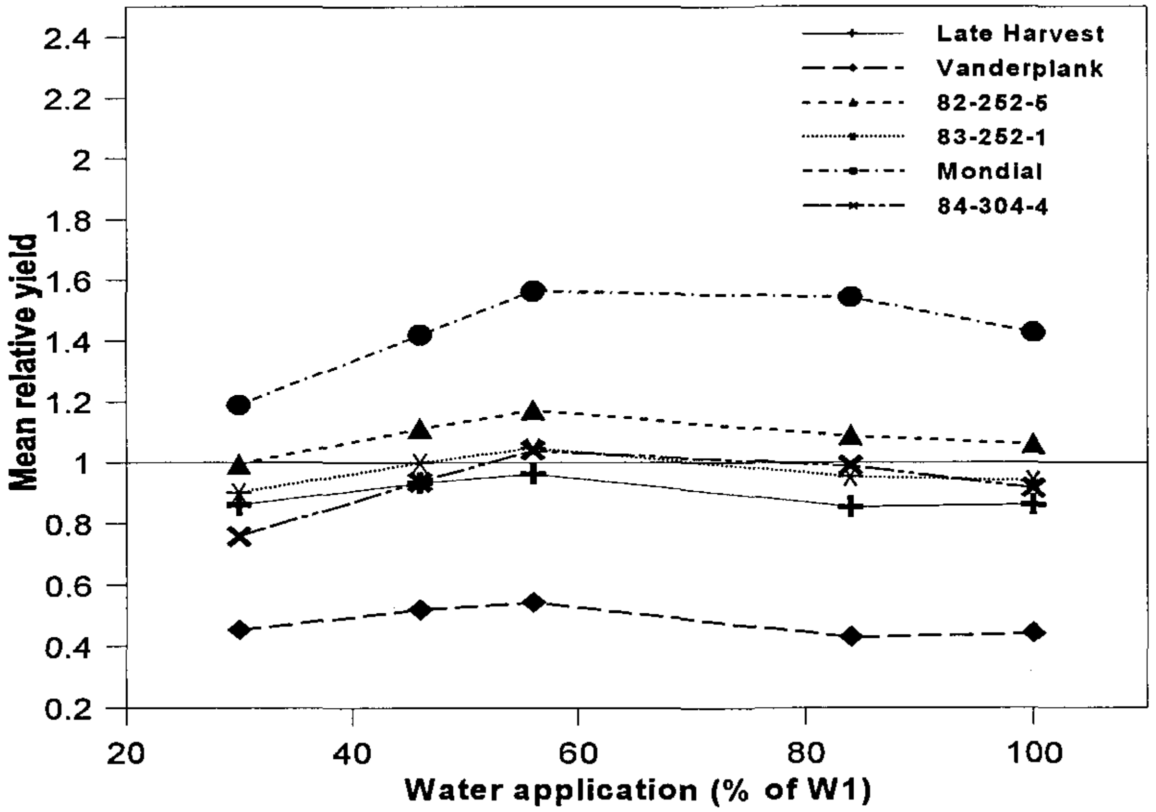


FIGURE 4.10 : Relative water-yield curves (relative to Up-to-date) of six medium potato genotypes exposed to five levels of water stress during the 1993 to 1995 autumn seasons.

For the medium-maturity genotypes the interactions between water treatments and genotypes were not significant for the autumn plantings, as was the case with the late genotypes. The main effects were, however, significant (summary of the ANOVA presented in Table B7 of the Appendix. The mean relative yield at all the water treatments grouped around one (Figure 4.9), indicating that the average yield of the genotypes did not differ much from that of Up-to-date for the same water treatment. The absence of trends over water treatments is clearly illustrated by the relative production functions (Figure 4.10). The ranking of genotypes was therefore not affected by water treatments, as was the case with the late genotypes. Mondial consistently had the highest yield and Vanderplank the lowest.

4.3.2 Tuber-size distribution

Late genotypes In general, the bulk of the total yield was made up from the yield of medium size tubers during the spring plantings (Figure 4.11). The relative proportions of the different sizes were influenced by year effects, as is clear from the size-distribution data of Late Harvest over the three spring plantings. Although the total yields were fairly stable around 50 Mg ha^{-1}, the wetter treatments had a higher proportion of large tubers in 1993 than in other years. In 1994 there was a tendency for more small tubers to be produced at all water levels; this was conspicuous for Late Harvest, and even more so for 83-363-67. The yield of small tubers was apparently not influenced by water treatments, remaining fairly constant in all genotypes. The yield of large tubers was the first to be reduced by water stress and for the most stressed treatment (W5), hardly any large tubers were produced by any of the genotypes.

The rate of decline in yield with increased water stress seems to be lower for medium than for large tubers and there are indications of genotypic differences in declining total yield with water stress. With the genotypes Late Harvest and Vanderplank, for instance, there seems to be a lower rate than for Up-to-date and Mnandi. This phenomenon is discussed later as a possible measure of drought tolerance (Chapter 9). Water stress did not result in marked differences in tuber-size distribution of genotypes, although 83-363-67 produced few large tubers for treatments drier than W2. The lowest yields were produced by 84-304-4, where population problems were encountered due to physiologically young seed tubers.

The total yields in autumn were generally only slightly lower than in spring plantings (Figure 4.12). The autumn of 1995 was, however, an exception, and very low yields were produced by all the genotypes. This was probably attributable to less solar radiation being intercepted by plants due to a cloudy season. The class A-pan evaporation for the 1995 autumn totalled ca. 400 mm, compared with the average of 525 mm for the other autumn plantings covered in this study. The proportion of large tubers appeared to be slightly lower than in the spring plantings for all genotypes. The rate of decline in total yield with increasing water stress appeared to be more gradual than in spring plantings, possibly because of the lower atmospheric evaporative demand in autumn. Genotypic differences were also not as obvious.

Medium and early genotypes Total tuber yield of all the genotypes generally declined as less water was applied (Figure 4.13). Tuber-size distribution was dependent on year effects, as was the case with the late genotypes. During the 1994 spring planting, conditions were conducive to the production of more small tubers and fewer large tubers, a phenomenon also observed for the late genotypes. The medium-size tuber yield made up the largest proportion of the total yield in all genotypes. There were definite genotypic differences in the rate of decline in total yield with increased water stress. The tuber-size distribution of genotypes was apparently not influenced differently by water stress during spring plantings, as within the same year, all genotypes followed trends similar to that of the standard cultivar (Up-to-date).

Apart from the autumn 1995 planting, when yields were very low, total yield differences between spring and autumn plantings were relatively small, except for the two early genotypes Vanderplank and 83-252-1, which had considerably lower yields in autumn than in spring plantings (Figures 4.13 and 4.14). For all cultivars, the decline in yield of large and medium tubers was more gradual in autumn than in spring plantings. The lower atmospheric evaporative demand in autumn presumably induced lower levels of plant water stress, which resulted in the production of more large and medium-sized tubers than in spring plantings.

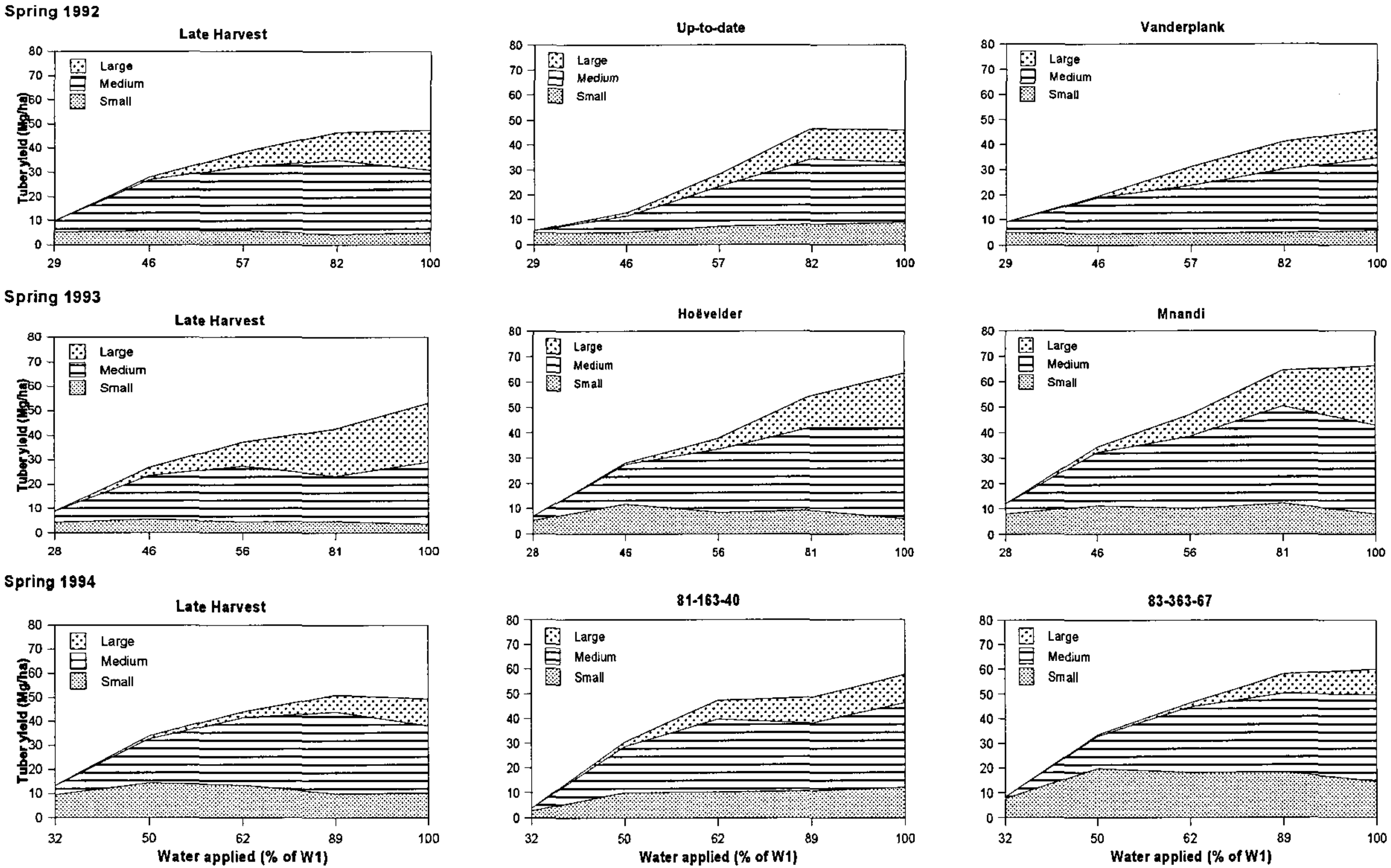


FIGURE 4.11: Tuber-size distribution of late genotypes as influenced by five water treatments in the 1992 to 1994 spring seasons. Note: X-axis not linear

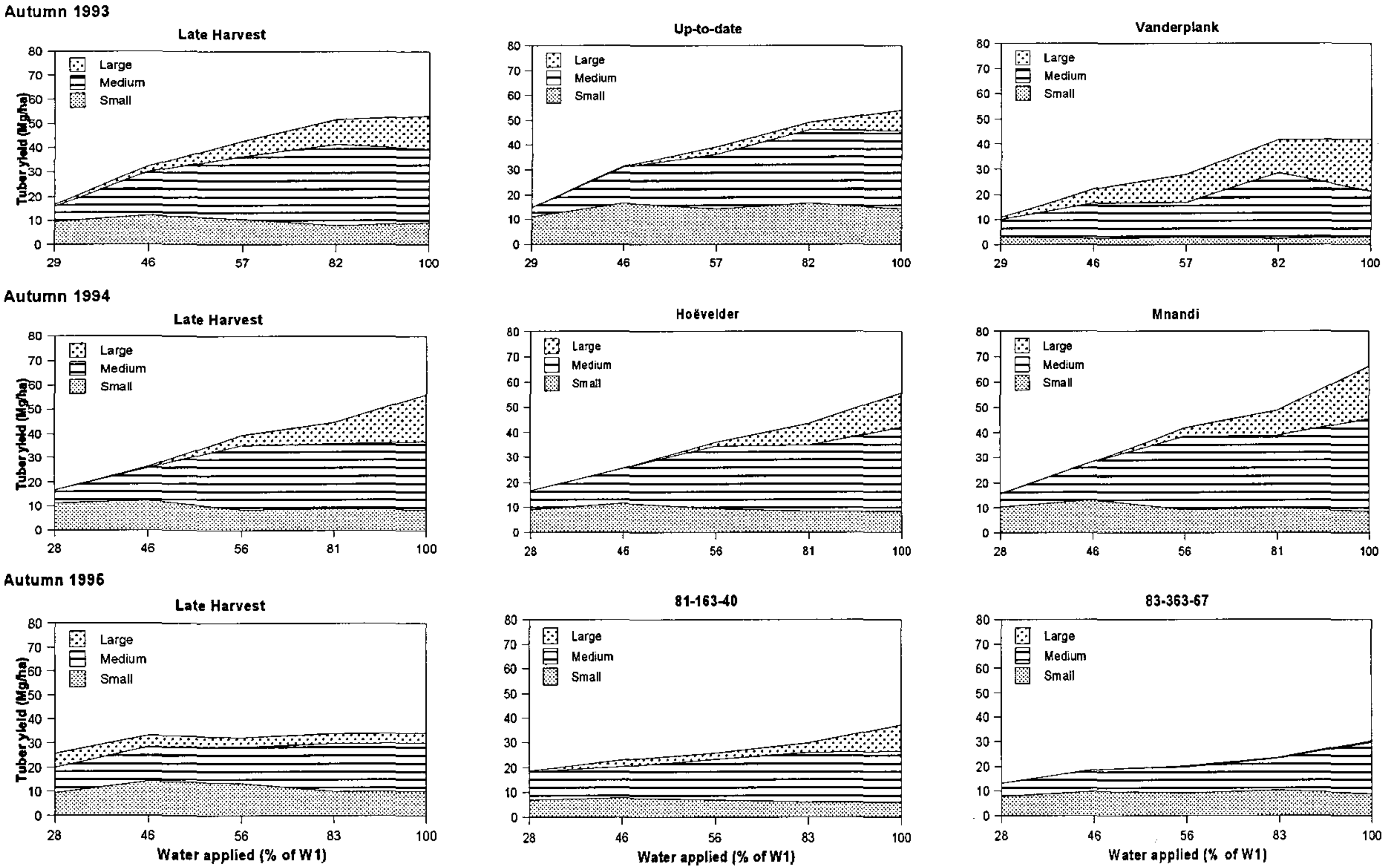


FIGURE 4.12: Tuber-size distribution of late genotypes as influenced by five water treatments in the 1993 to 1995 autumn seasons. Note: X-axis not linear

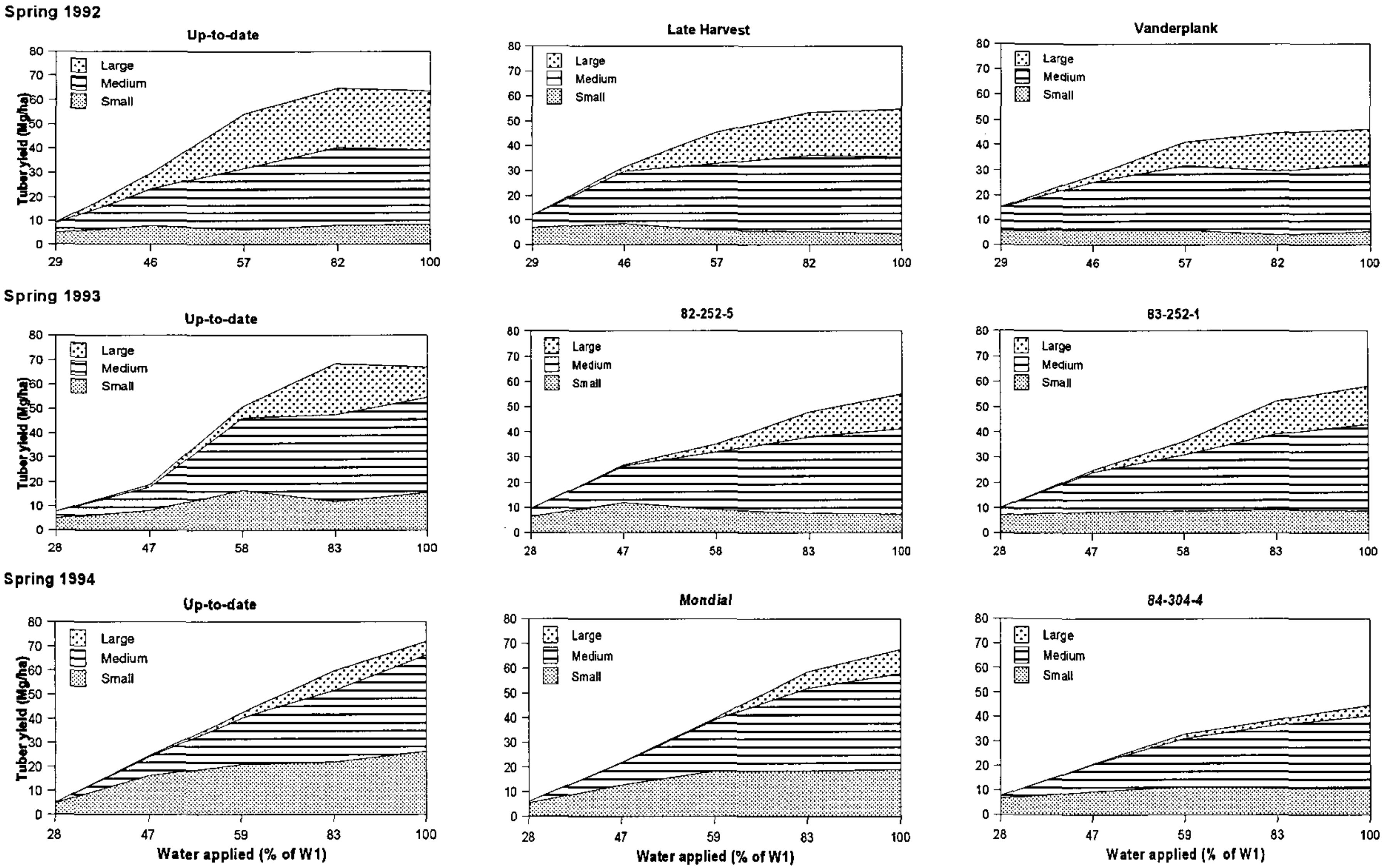


FIGURE 4.13: Tuber-size distribution of medium genotypes as influenced by five water treatments in the 1992 to 1994 spring seasons. Note: X-axis not linear

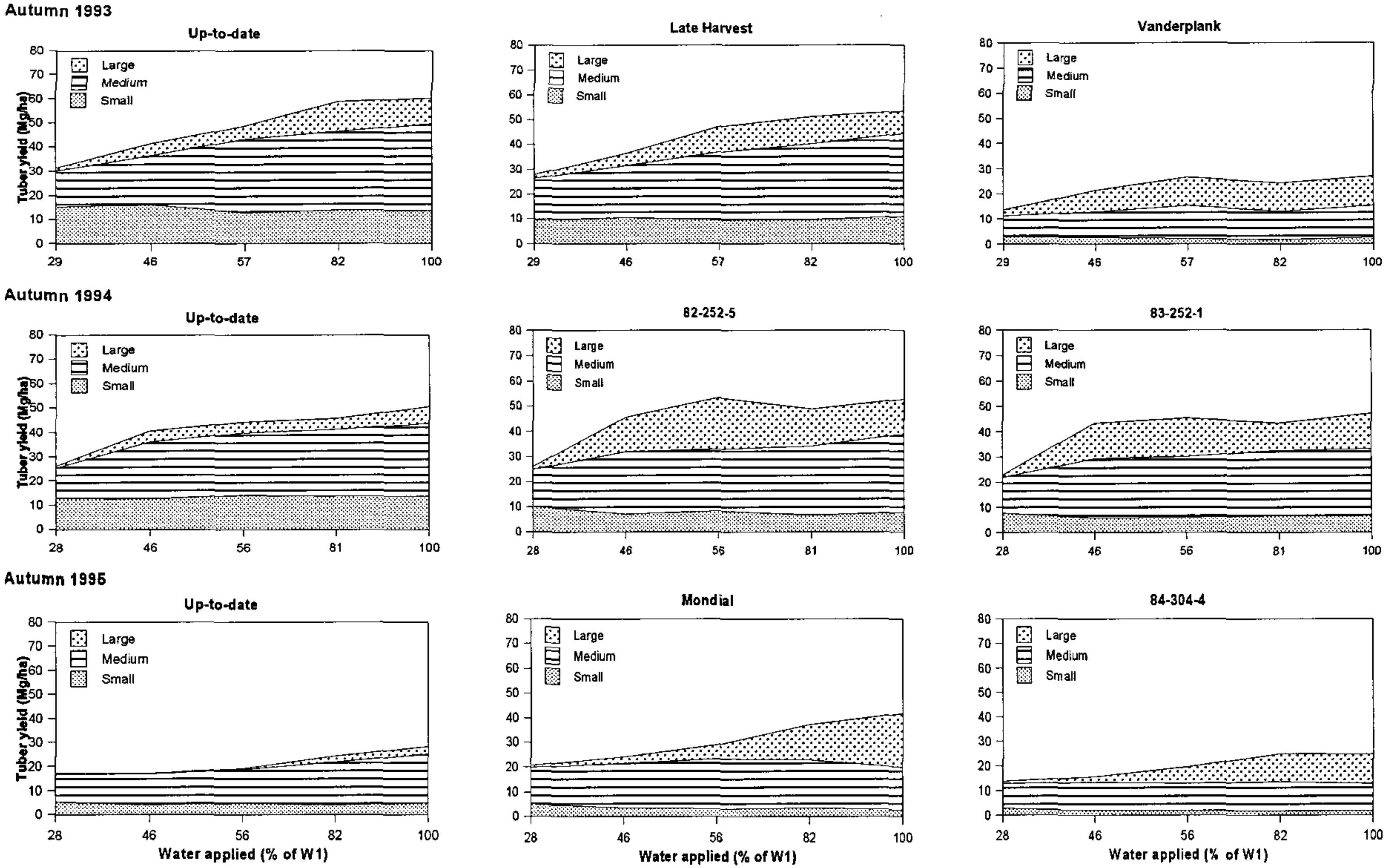


FIGURE 4.14: Tuber-size distribution of medium genotypes as influenced by five water treatments in the 1993 to 1995 autumn seasons. Note: X-axis not linear

For most of the genotypes total yield for W5 in spring plantings was more than double that in autumn. The breeding lines 82-252-5 and 83-252-1 showed almost no decline in yield of medium and large tubers when water supply was reduced from W1 to W4.

4.4 Discussion

The responses of genotypes to levels of water supply were dependent on plantings, with the effect of drought on total yield and tuber-size distribution more detrimental in spring than in autumn plantings. The yields from well watered treatments generally did not differ much between plantings (spring and autumn), with the exception of the 1995 autumn planting, when yields were very low. Levy *et al.* (1990), however, have reported substantially lower yields in autumn than in spring for subtropical conditions, essentially similar to those of Roodeplaat, resulting from decreasing temperature, day length and irradiation levels (Table 3.1). Many cultivars included in their trials were of European origin and may therefore be sensitive to the shorter autumn days. Surprisingly, in the present trials only the yields of the early genotypes 83-252-1 and Vanderplank were lower in the shorter autumn season than in spring, indicating their possible sensitivity to short day conditions.

In autumn, the ranking of genotypes according to yield was not influenced by water stress, but rather by genetic potential and adaptability to climatic conditions. Genotypes adapted to the autumn season need a capacity for early tuberization and tuber growth under high temperatures, and the maintenance of effective haulm growth (Levy *et al.*, 1990), as short days generally prevent flowering, promote tuber initiation and hasten crop maturity (Ezekiel, Perumal & Sukumaran, 1987).

Yield losses as a result of water stress were much higher in spring than in autumn plantings. In spring plantings, the effect of water stress might be aggravated by higher temperatures (Levy *et al.*, 1990) and, possibly, by the higher atmospheric evaporative demand as summer sets in (Trebejo & Midmore, 1990). In spring plantings genotypic differences in response to drought were recorded for both maturity classes. In the wetter treatments the ranking of genotypes remained unchanged and yield was dependent on genetic potential, but the ranking changed as stress increased in both maturity classes. Late Harvest, the standard cultivar in the late maturity class, was one of the better performers under drought conditions. This agrees with the findings of Van der Mescht *et al.* (1992), who used biochemical screening techniques to classify the drought tolerance of potato genotypes. Up-to-date, the medium standard cultivar, was one of the more drought-sensitive cultivars, as it had the largest reduction in yield due to drought. In a study by Jefferies & MacKerron (1993), Up-to-date was also among the cultivars that showed the highest degree of yield reduction as a consequence of drought. The medium to late genotypes had the highest yield potentials, while the early cultivar Vanderplank had the lowest average yields. The genotype 84-304-4 performed unsatisfactorily in both plantings due to external factors and should be further evaluated before any conclusions can be drawn regarding the effect of water stress on its performance.

Certain of the genotypes that had high yield potentials under optimal conditions (e.g. Up-to-date and Mondial) produced the lowest yields when stressed. This often happens as most of the adaptation traits that favour survival under stress conditions tend to reduce potential yields (Begg & Turner, 1976 according to Levy *et al.*, 1990). On the other hand, some of the genotypes that produced the lowest yields under optimal conditions, had the highest yields when stressed (e.g. Late Harvest). These findings contradict the conclusion of Jefferies & MacKerron (1993) that there is limited capacity for improvement in drought tolerance through breeding, other than through improvements in potential yield. In some cases high yield potentials did compensate for sensitivity to drought. Hoëvelder is a typical example in this regard: it showed sensitivity to drought but, because of its high yield potential, produced the same or higher yields than Late Harvest for all water treatments, with the exception of W5. Mnandi had a very high yield potential in summer, while also showing drought tolerance similar to that of Late Harvest. Drought tolerance is not related to maturity class, as some genotypes representative of all the maturity classes showed the ability to withstand drought. This suggests that drought tolerance is also not only attributable to drought escape by early genotypes, as is often reported in literature.

The yield of medium, but especially large tubers, was influenced negatively by water stress. This trend was also recorded by MacKerron & Jefferies (1988), who reported a downward shift in size distribution because of drought. Medium-sized tubers made up the bulk of total yield in all maturity classes and plantings. The negative effects of water stress on size distribution were less severe in autumn plantings, as was the case with total yield. Tuber size appeared not to be influenced differently by water stress in most of the genotypes. However, the two genotypes 82-252-5 and 83-252-1 were able to maintain high yields of medium and large tubers down to the W4 water supply level.

The physical yield of small tubers was not increased by water stress. In the drier treatments the yield of small tubers made up a greater proportion of the total yield, due to the fact that the medium and large yield decreased.

Some of the variation in the proportion of large to medium tubers may not only be attributable to external factors such as drought, but may also be as a consequence of the arbitrary boundaries that were set for the separation of classes. The difference between medium and large tubers, especially, may have caused some variation as tubers of 249 g were considered to be medium, while tubers of 250 g and heavier were recorded as large. In small-plot trials such as these, a few tubers just below or above the cut off margin may lead to a total distortion of the data, as the large tubers contribute significantly to the total mass.

4.5 Conclusions

The negative effects of drought on tuber yield and size distribution were more severe in spring than in autumn plantings, presumably because of the higher atmospheric evaporative demand and higher temperatures in spring plantings. The ranking of genotypes according to tuber yield was dependent on the water regime in spring plantings, while in autumn the ranking was unchanged and mainly determined by the genetic potential of genotypes. This implies that the selection of genotypes by the potato producer should be based on the availability of water in spring, but not in autumn plantings. Drought-sensitive genotypes, such as Up-to-date, Mondial and 81-163-40 should be avoided where water stress is expected during spring plantings.

In the late-maturity class Late Harvest, Mnandi and Hoëvelder perform best when water supply is limited. Mnandi will also produce high yields with ample water. In the medium-maturity class Vanderplank, 83-252-1 and 82-252-5 should produce good yields under drier conditions, while Up-to-date and Mondial are the most sensitive to limited water supply. When water is non-limiting the latter two cultivars have high yields and should be used.

Water stress lowered the yield of large and medium tubers in all genotypes, but genotypic differences were small. The effect of water stress on tuber size distribution and total tuber yield was more detrimental in spring plantings. The disadvantageous downward shift in tuber size because of drought may be of lesser concern to seed producers, who strive for tuber sizes of between 50 g and 120 g (small to medium), but it should be kept in mind that total tuber yield will also be reduced as a consequence of water stress.

In the current study, local potato genotypes have for the first time been characterised according to their performance at different levels of water supply. This should assist the potato producer in the selection of genotypes most suitable for his farming conditions, considering the growing season and available water supply.

CHAPTER 5

THE EFFECT OF WATER REGIMES ON INTERNAL TUBER QUALITY

5.1 Introduction

Water stress affects both internal and external potato tuber quality, aspects that have received considerable attention in research programmes (Van Loon, 1986; Adams & Stevenson, 1990; Ojala *et al.*, 1990; Jefferies & MacKerron, 1993; Shock, Holmes, Stieber, Eldredge & Zhang, 1993; Trebejo & Midmore, 1990). Interrupted irrigation during the tuber bulking phase may lead to lower external quality due to disorders such as secondary growth, growth cracking and knobby tubers (Adams & Stevenson, 1990). Two important internal quality characteristics commonly affected by water supply are tuber dry matter and reducing sugar content.

Tuber dry matter and reducing sugar content are especially important if tubers are intended for processing: The yield of crisps, a processed tuber product, is dependent on the dry matter content of the tubers, since crisping is a dehydration process (Logan, 1989). Lower dry matter percentages therefore directly relate to losses in income. Chip colour, one of the most important quality attributes in the potato processing industry (Orr & Janardan, 1990), depends on the reducing sugar content of tubers. Tubers containing high concentrations of reducing sugars produce fries and crisps that are unacceptably dark in colour.

The dry matter content of tubers at harvest is influenced by various factors during the growing season. Dry matter content tends to increase progressively during the growth of the crop to reach maximum values at maturity (Jewell & Stanley, 1989; Ojala *et al.*, 1990), but the pattern of increase varies greatly between crops and years, and the final value at harvest is influenced by cultivar, cultural practices and the environment (Jefferies *et al.*, 1989). In drought-stressed crops the dry matter content of tubers is usually increased (Marutani & Cruz, 1989; Trebejo

& Midmore, 1990; Jefferies & MacKerron, 1993), because water stress affects tuber water content to a greater extent than dry matter accumulation (Jefferies *et al.*, 1989). Ojala *et al.* (1990) observed reduced tuber relative densities as a result of interrupted irrigation, while the effect of declining irrigation on relative density was small and inconsistent (Miller & Martin, 1987b).

Dry matter accumulation in tubers is also dependent on temperature during the growing period of the crop. It is favoured by increasing temperatures up to an optimum of about 18°C (Van Heemst, 1986). At higher temperatures the partitioning of dry matter to the tubers is inhibited (Van Heemst, 1986) and the dry matter content of tubers is therefore reduced (Levy, 1984). According to Jefferies *et al.* (1989) variations in tuber dry matter content are best accounted for by a regression model that is a function of soil-water deficit and the accumulation of thermal time above a base of 0 °C from the time of emergence. They reported that increasing temperatures and soil-water deficits favoured higher dry matter contents. However, this model is based on studies in a temperate climate and may not be applicable to hot climates, as Jefferies *et al.* (1989) have pointed out.

The browning of potato chips occurs as a result of non-enzymatic reactions, involving reducing sugars and amino acids, the so-called Maillard reaction (Iritani & Weller, 1977; Owings *et al.*, 1978). Glucose is considered the most important reducing sugar in determining chip fry colour (Brown *et al.*, 1990; Coleman *et al.*, 1993; Coles, Lammerink & Wallace, 1993).

Under normal growing conditions the levels of reducing sugars fall as the crop matures (Iritani & Weller, 1977; Jewell & Stanley, 1989; Richardson, Davies & Ross, 1990a; Richardson *et al.*, 1990b). In some cases abnormally high sugar accumulation occurs in tubers because of unfavourable conditions during growth of the potato plants. These conditions include a lack of soil water, high fertiliser applications late in the growing season, premature vine-death and excessively high or low temperatures (Miller 1975, in Jewell & Stanley, 1989; Owings *et al.*, 1978; Sowokinos, 1990).

Reducing sugars start to accumulate in tubers at temperatures below 10 °C (Dogras, Siomos

& Psomakelis, 1991) as a result of the conversion of starch to free reducing sugars (Harris, 1978; Sowokinos, 1990). High mid-season soil temperatures are reported to increase sugar-end tubers (Kincaid, Westermann & Trout, 1993). Kincaid *et al.* (1993) were able to lower high soil temperatures by increasing the frequency of irrigation, but the amount of irrigation did not affect soil temperature or tuber quality. Logan (1989), however, could not find any differences in reducing sugar content as a result of different irrigation frequencies.

The mechanisms responsible for stress-induced sweetening of potato tissue are still to be explained at the molecular level. This is not surprising, since the production of free sugars in cells is not regulated by a single factor (Sowokinos, 1990).

Little is known about the effects of environmental conditions and cultivation practices on tuber relative density and reducing sugar content of South African potato cultivars. Although aspects such as chip colour are only of major concern to the processing industry, tuber relative density is also important to the table potato market, as it gives a general indication of tuber keeping quality. In this study the effects of different soil-water regimes on tuber relative density and chip colour were determined for some local potato genotypes in both spring and autumn plantings.

5.2 Materials and methods

Observations on quality aspects were made on the tubers obtained from irrigation trials carried out during the spring 1993 to autumn 1995 plantings. Cultivation practices and treatments applied in the trials are fully described in Chapters 3 and 4. After harvest, the tubers were graded into different size classes and weighed. Ten medium-sized tubers from each plot were randomly selected and checked for external defects. The samples were weighed in air and water, and the relative densities calculated by dividing the mass in air by the difference between the masses measured in air and water (Logan, 1989; Kincaid *et al.*, 1993). Five slices (1.5 mm thick) were cut from the stem-ends of each of the ten tubers. The slices were briefly rinsed in water and blotted with towels before being fried in vegetable oil at initial temperatures of 190 °C. Frying was continued for approximately 3.5 minutes, until bubbling subsided and the chips were crisp (Ewing, Senesac & Sieczka, 1981). The fried chips were drained and allowed to cool, before they were placed in brown paper bags and gently crushed. A Model D25L-2 Hunterlab colorimeter was used for chip colour determinations according to the method described by Scanlon, Roller, Mazza & Pritchard (1994), with the exception that the chip samples were crushed before measurement.

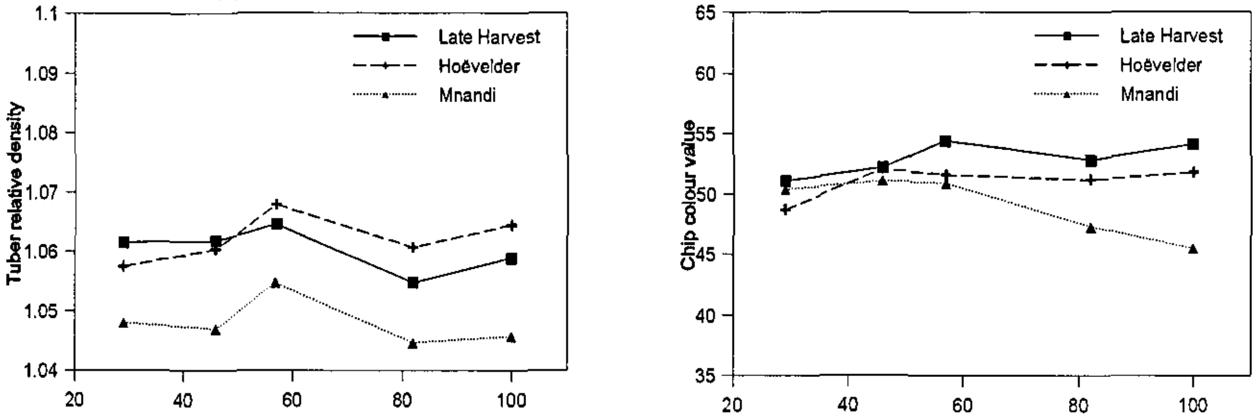
5.3 Results

Tuber relative density

Results for late and medium genotypes are presented separately in Figures 5.1 (a-d) and 5.2 (a-d). Marked seasonal differences in tuber relative densities were observed. In spring plantings tuber densities were generally lower than in autumn (for the same genotypes). No clear trends were observed as a result of water treatments in spring, while in most autumn plantings tuber densities decreased with increase in water supply. There were no interactions between genotypes and water treatments (Tables B8 and B9 of the Appendix), suggesting that genetic characteristics played an overriding role, since the ranking of genotypes according to their densities remained almost the same, independent of water treatment and planting. Of the late genotypes only Hoëvelder, a processing cultivar, had higher tuber densities than Late Harvest, the standard. Mnandi consistently had very low tuber densities, especially in the spring planting. Small differences were observed between genotypes in the medium maturity class. The two breeding lines intended for processing, 82-252-5 and 83-252-1, which were expected to produce high tuber densities, did not differ from Up-to-date in either planting. Unlike the tendencies in other autumn plantings, there was no trend over water treatments in the 1994 autumn planting, but tuber densities were consistently high for that planting. Mondial was the only cultivar that showed consistently lower tuber densities than the standard, Up-to-date.

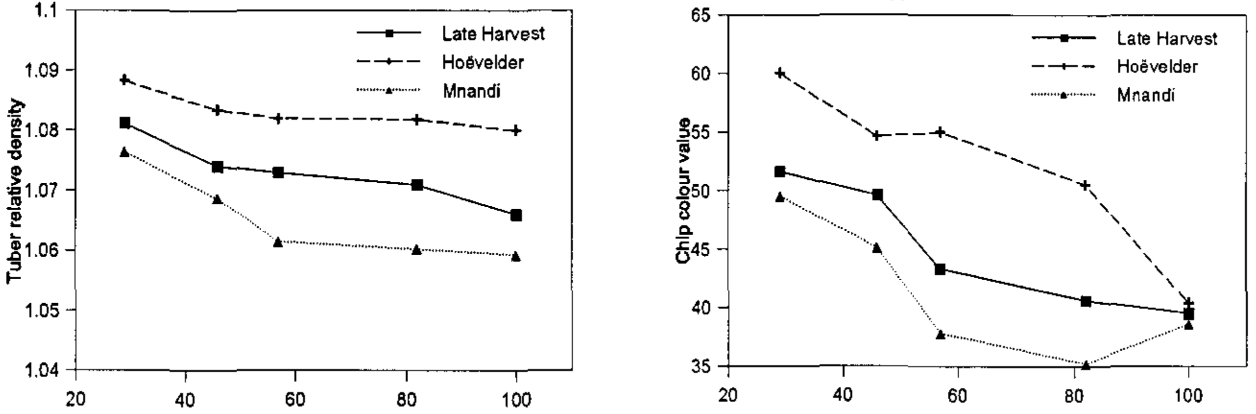
(a) Spring 1993

(e) Spring 1993



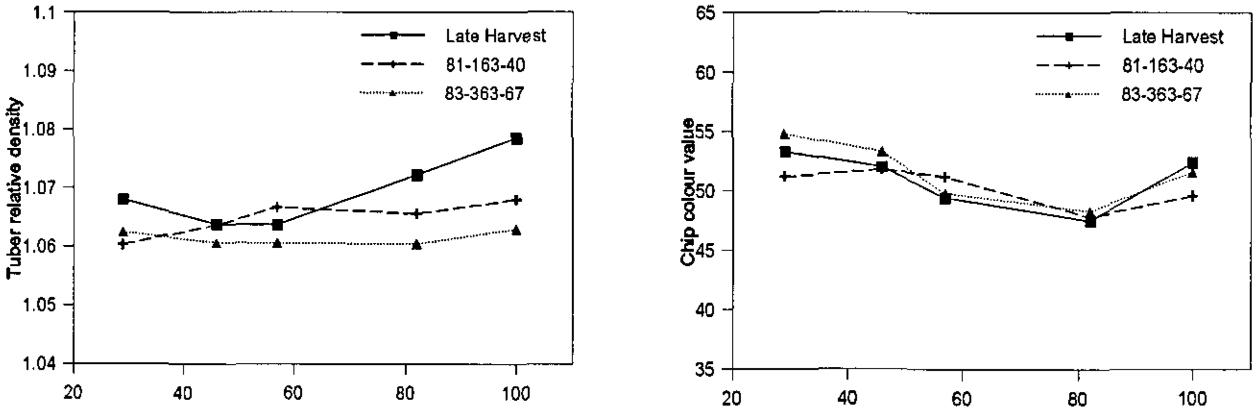
(b) Autumn 1994

(f) Autumn 1994



(c) Spring 1994

(g) Spring 1994



(d) Autumn 1995

(h) Autumn 1995

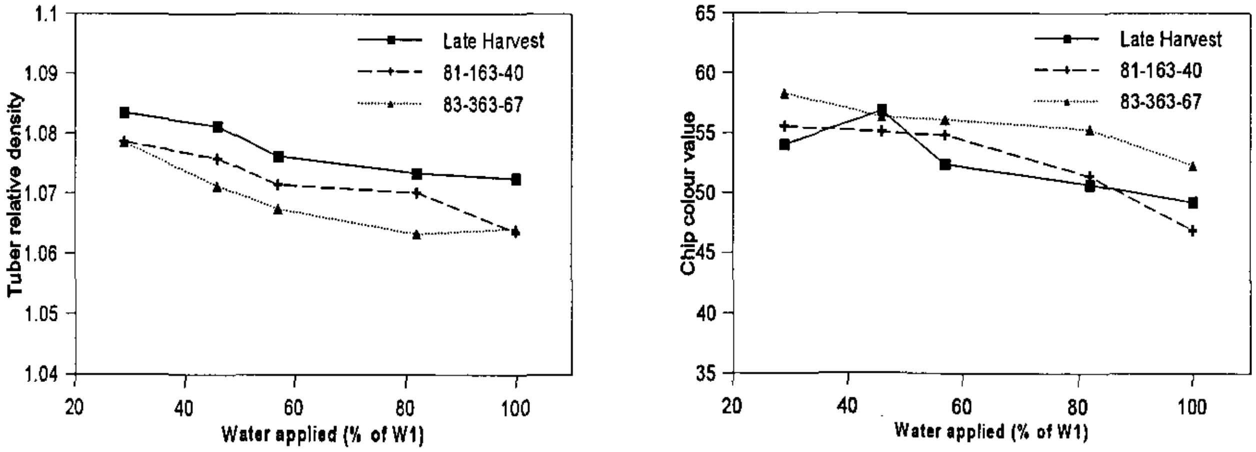


FIGURE 5.1 : The effect of five water regimes on tuber relative densities (a-d) and chip colours (e-h) of late genotypes in spring and autumn

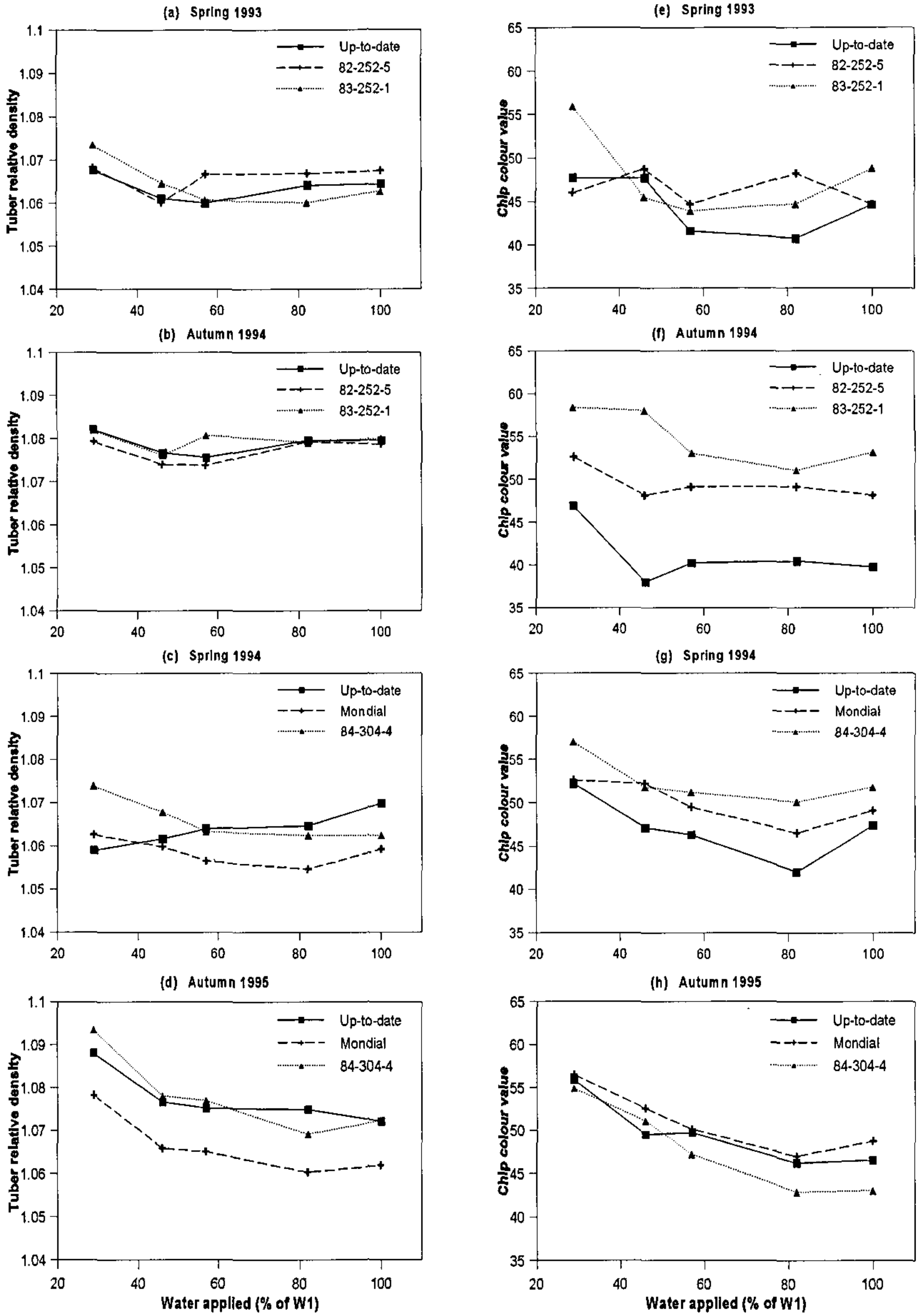


FIGURE 5.2 : The effect of five water regimes on tuber relative densities (a-d) and chip colours (e-h) of medium genotypes in spring and autumn

Chip colour

Chip colour results are presented in Figures 5.1 (e-h) and 5.2 (e-h) for the late and medium maturity classes, respectively. Chip colour values of 50 and higher are considered acceptable for processing. In most of the trials, with the exception of one spring planting, trends in response to irrigation treatments were evident. These trends were more pronounced for the autumn plantings, but the interactions between genotypes and water regimes were not significant for any planting (see Tables B10 and B11 of the Appendix for summarised ANOVAs). For both the late- and medium-maturity classes chip colour generally deteriorated with an increase in water supply. Most of the genotypes produced acceptable chip colours in the drier treatments in all plantings. In autumn plantings chip colours were not always better than in spring for the same irrigation treatments, as was the case with relative densities. Chip colour results of genotypes were not stable over plantings: the best chip colours were not produced by the same genotypes in spring and autumn plantings.

5.4 Discussion

Trends regarding tuber relative densities were dependent on seasonal effects. In autumn plantings the tuber relative densities of all the genotypes generally increased as less water was applied. This trend is expected as the water content of tubers is dependent on the water content of the surrounding soil (Jefferies *et al.*, 1989) and agrees with the results obtained by Marutani & Cruz (1989), Trebejo & Midmore (1990) and Jefferies & MacKerron (1993). The absence of trends in this study in tuber relative densities as a result of water treatments in the spring plantings is unexpected and contrary to most reports in the literature.

High ambient temperatures are known to have negative effects on tuber dry matter content (Hartz, 1978; Van Heemst, 1986), and therefore on tuber relative density: Yamaguchi, Timm & Spurr (1964) (according to Kincaid *et al.*, 1993) have found that specific gravity and starch content were highest and sugar content lowest when potatoes were grown at soil temperatures between 15 °C and 24° C. According to Jefferies *et al.* (1989) and Van Heemst (1986) optimum air temperatures for dry matter allocation to the tubers are between 18 and 20 °C. Higher air and soil temperatures in spring plantings may therefore explain the lower tuber densities observed in these plantings.

Soil temperatures were not recorded during the execution of the present study, but are known from literature to be a function primarily of air temperature and radiation (Kincaid *et al.*, 1993). The average air temperatures recorded during the tuber bulking phase were between 2 °C and 7 °C warmer in spring plantings (October to December) than in autumn (April to May) (see Figure 3.1). Air temperatures during the bulking phase were therefore higher than the optimum on most days in the spring plantings, while in autumn it was only the case during the early tuber bulking phase (first part of April) of some plantings.

Soil temperatures are to a lesser extent also influenced by factors like shading of the soil surface and soil-water content (Kincaid *et al.*, 1993). In the wetter treatments it was expected that higher soil-water content and a higher degree of soil cover by larger crop canopies would have beneficial effects on soil temperature in spring plantings. This does not seem to be the case, as the relative densities of wetter treatments were no better than those of dry treatments. Kincaid *et al.* (1993) found that both amount and frequency of irrigation influenced soil temperatures, but that frequency had the largest effect. High frequency irrigation maintained lower soil temperatures, probably due to increased evaporation from the soil surface. In the present study the frequency of irrigation was the same for all treatments (only the amount of irrigation differed), which may explain the absence of trends in spring plantings. In autumn the temperature effect was negligible due to lower ambient temperatures during tuber bulking, and tuber relative densities were mainly determined by water supply.

Genotypic differences played an overriding role in the ranking of genotypes according to tuber relative density, independent of the planting and water regime applied. The relative densities of genotypes were also not influenced differently by water stress.

The effect of water stress on chip colour is still not clear. The results of the present study suggest that chip colour was apparently never affected negatively by water stress in any of the genotypes and plantings. This is in contrast to most published reports of darker stem-end (basal end) chip colours in water stressed environments (Owings *et al.*, 1978; Kincaid *et al.*, 1993; Shock *et al.*, 1993). Variable results between seasons and localities have, however, often been reported in the literature: Richardson *et al.* (1990a), for example, were not able to relate reducing sugar content to any factor other than harvest date, despite a range of environmental conditions and management practices, which included differences in soil temperature and total rainfall; Kincaid *et al.* (1993) did not consistently record better chip colours for wetter treatments, although high-frequency irrigation seemed to improve chip colour. The high frequency of irrigation in the present trials, even though application amounts were small, may therefore have improved the chip colours resulting from the dry treatments to the extent that they were similar to that resulting from the wet treatments in spring plantings.

High temperatures during tuber development are known to increase reducing sugar content (Owings *et al.*, 1978) and therefore to produce darker chips. In the spring plantings, the detrimental effects of high temperatures on chip colour appear to be balanced by the beneficial effects of regular irrigation. It also appears that reducing sugars start to accumulate at higher temperatures than those at which tuber relative densities are influenced negatively. The results are therefore that chip colours of water stressed treatments were no worse than those of unstressed treatments.

In autumn plantings, temperatures were generally lower during the tuber bulking phase, compared to spring plantings. Since chip colour generally improved with increasing water stress, the effect of high temperature on chip colour was clearly not a factor. As this trend is in contrast to most published findings, the possible effects of low temperatures experienced at the end of the season in the case of wet treatments should be investigated. Low temperatures late in the growing season have been reported to induce higher concentrations of reducing sugars in tubers (Miller, 1975 according to Jewell & Stanley, 1989). The reaction is similar to cold sweetening under low temperature storage (Gawad, Omer & Ahmed, 1990; Dogras *et al.*, 1991). Reducing sugars only start to accumulate at temperatures below 10 °C. Although in the present study minimum air temperatures dropped below 10 °C from the beginning of April, mean air temperatures lower than 10 °C were never experienced in autumn (Figure 3.1). In the absence of soil temperature measurements, only speculations can be made on the effect water regimes would have had on the micro climate, and therefore also on the soil temperature. It is likely that the lowest soil temperatures occurred at the wetter treatments, due to factors such as the higher thermal conductivity of wet soils, greater evaporative cooling and the fact that the soil surface was more completely covered by the canopies of unstressed plants, which reduced the portion of direct solar radiation absorbed by the soil surface. These lower soil temperatures may have resulted in the darker chip colours experienced in the case of wetter treatments.

Plant nutrition, especially the supply of nitrogen, is known to influence aspects of internal tuber quality, such as tuber relative density. Higher rates of nitrogen usually reduce relative density (Logan, 1989). In this study all water regimes received the same fertilisation programme and there is a possibility that some nutrients were supplied in excess or at sub-optimum levels for high quality. Differences in the rate of nutrient uptake could also be responsible for seasonal differences in tuber quality observed.

5.5 Conclusions

Tuber internal quality was dominated by temperature effects in both plantings. In spring plantings no trends with regard to tuber relative densities were observed, mainly because of the negative effect of high temperatures on dry matter content. In autumn plantings the dry matter content of tubers was increased with increasing water stress, as was expected. Genotypes did not respond differently to water stress.

Chip colour also showed no response to water stress in spring plantings, presumably as a consequence of high temperatures and the moderating effect of high frequency irrigation. In autumn plantings, expectations arising out of literature, of chip colour deterioration with increasing water stress were not realised. In fact, the contrary was true. The frequent application of water probably helped to cool down the soil during the tuber bulking phase in autumn, with temperatures of soils in wet treatments probably being lower than those of the dry treatments. Low-temperature sweetening, a familiar phenomenon encountered in cold storage, thus apparently occurred in the wet treatments, resulting in darker chips. Genotype X water interactions were not significant, indicating that although main effects were significant, genotypes did not respond differently to water treatments.

These results show a conflict between the highest tuber yield and best tuber quality, as the treatments that produced the highest tuber yield generally produced the lowest tuber quality. Producers will therefore have to balance their irrigation scheduling to find the best compromise between highest tuber yield and quality. In this study the intermediate water regimes (W3 to W2) seemed to provide the best compromise between high yield and good tuber quality.

For future water-use studies it is recommended that soil temperatures and the nutritional status of plants should be monitored in order to quantify their complicating effects on internal tuber quality.

CHAPTER 6

THE USE OF PHYSIOLOGICAL PARAMETERS IN SCREENING FOR DROUGHT TOLERANCE

6.1 Introduction

Drought stress is recognized as a major constraint to potato production (Van Loon, 1981; Jefferies, 1983a; Dwelle, 1985; Van Loon, 1986). Tuber yield is determined by the interaction of a number of physiological processes such as photosynthesis, leaf expansion, leaf senescence, tuber initiation, and the partitioning of assimilates (Schapendonk *et al.*, 1989), all of which are affected by water stress, generally resulting in lower tuber yields (Coleman, 1986).

Stomatal closure in response to water stress reduces the rates of transpiration and photosynthesis, which may lead to decreased yield. The stomata of potato plants are reported to close at relatively high leaf water potentials compared to other crops (Van Loon, 1981), and reductions in stomatal conductance caused by water stress have frequently been reported for potatoes (Rutherfoord & De Jager, 1975; Dwelle, 1981a; Dwelle 1985; Bansal & Nagarajan, 1986; Vos & Groenwold, 1988; Ezekiel, Perumal & Sukumaran, 1989). In fact, stomatal resistance has been found to be a sensitive indicator of water stress in many crops, including potatoes (Rutherfoord & De Jager, 1975; Oosterhuis & Walker, 1987) and is also a promising aid in screening for drought tolerance in potato genotypes (Wilcox & Ashley, 1982).

The photosynthetic process has been found to be very sensitive to water stress in crops such as maize, and measurements of photosynthetic rate have given a good indication of water stress (Ceulemans *et al.*, 1988). The influence of water stress on the photosynthetic rate of potatoes has been investigated thoroughly (Munns & Pearson, 1974; Shimshi *et al.*, 1983; Dwelle, 1985, Vos & Groenwold, 1989). Although stomatal conductance responds earlier to water stress than photosynthetic rate, photosynthesis has also proved to be a good indicator of water stress in potato plants (Bodlaender *et al.*, 1986; Van Loon, 1986; Vos & Groenwold, 1989). Marked differences in assimilation rate have been recorded between genotypes and plantings (Dwelle *et al.*, 1981; Moll, 1983). However, attempts to correlate stomatal conductance (or resistance) and photosynthetic rate with tuber yield have not been very successful. The reason for the poor correlations is that tuber yield is determined not only by the photosynthetic rate of single leaves, but also by factors such as total canopy assimilation, and the partitioning of assimilates to different plant organs (Dwelle *et al.*, 1981). However, in spite of the poor correlations sometimes recorded between short-term photosynthetic rate and yield, high photosynthetic rates are nonetheless essential to achieve high yields (Dwelle, 1985).

Despite the above mentioned reservations, various authors have investigated single-leaf photosynthetic rate as a screening method for drought tolerance in potato plants: Sukumaran *et al.* (1989), for example, reported drought-induced reductions in photosynthetic rates of 32% for drought-tolerant and 84% for drought-susceptible genotypes; and Schapendonk *et al.* (1989) recorded the greatest reduction in photosynthetic rate as a result of water stress in a drought-sensitive cultivar. Reports in this regard are, however, not consistent: in the same trial conducted by Schapendonk *et al.* (1989), other cultivars which differ in their drought tolerance varied little in their photosynthetic response to water stress. Wilcox & Ashley (1982) have also shown that there is no consistent reduction in photosynthetic rate attributable to stress treatments among the different potato cultivars they studied. Schapendonk *et al.* (1989), therefore concluded that gas exchange measurements at a certain developmental stage can at best only explain part of the variation in drought tolerance encountered in the field.

The objective of this facet of the study was to relate photosynthetic rate and stomatal resistance of potato genotypes exposed to water stress to yield response. Field screening for drought tolerant genotypes is arguably the best method of selection, but it is tedious and expensive, and only a limited number of genotypes can be evaluated simultaneously. This has prompted a search for reliable techniques suitable for the early selection of large numbers of potentially drought-tolerant parental material. Most of the published research in this field has focussed on single or short-term measurements of photosynthetic rate at certain physiological stages. For this reason the possibility was explored of using mean seasonal photosynthetic rate and stomatal resistance in stressed and unstressed conditions as indicators of drought tolerance in potato genotypes.

6.2 Materials and methods

Information on the cultivation practices and water treatments applied during the execution of the trials is described in detail in Chapters 3 and 4. Physiological measurements were made during the 1992 autumn, 1992 spring and 1993 spring plantings.

Gas exchange measurements were made periodically throughout the growing season between 10:00 and 12:00, but only on days when the photosynthetically active radiation (PAR) was higher than 1000 μmol m^{-2} s^{-1}. Due to the fact that measurements were not necessarily made at comparable stages within each irrigation cycle, the data of different plantings could not be compared. Comparisons between genotypes within the same season were, however, justified as measurements were carried out on the same days.

An LI-6250 portable photosynthesis system (LI-COR Ltd., Lincoln, USA) with a 1000 cm^3 leaf chamber was used to carry out measurements on intact leaves. Leaf area inserts were used to limit the exposed leaf area to 8 cm^2. All measurements were on the terminal leaflet of the third to fifth expanded leaf from the top of the plant. Only sunlit leaves were used and after insertion, the leaf chamber was positioned so as to ensure continued exposure of the adaxial leaf surface to maximum sunlight. Two to three measurements per plot were made on two replications of the trial. The 15-second measurements started immediately after a constant reduction in CO_2 concentration was observed. Leaf photosynthesis, transpiration and stomatal resistance were calculated from these measurements.

During 1992, data were recorded on 17 occasions for the autumn planting, and on 18 occasions for the spring planting. Only eight observations were possible during the 1993 spring planting due to the high number of cloudy days. In the case of the early to medium maturity class cultivars, which senesce earlier, fewer measurements were possible. During the 1992 autumn planting measurements were carried out only on the W1, W3 and W5 treatments.

6.3 Results and discussion

Both photosynthetic rate (Pn) and stomatal resistance (Rs) responded to water regimes in all plantings. Genotypes showed increased stomatal resistance and decreased rates of photosynthesis because of water stress, as has frequently been reported (Rutherfoord & De Jager, 1975; Dwelle *et al.*, 1981a; Dwelle 1985; Bansal & Nagarajan, 1986; Vos & Groenwold, 1988; Ezekiel *et al.*, 1989). All the genotypes in the present study revealed similar trends over the growing period; only the photosynthetic response of Late Harvest to water stress is therefore presented graphically as an example (Figure 6.1).

A considerable degree of variation in Pn and Rs was evident for all treatments possibly due to changing weather conditions. Under non limiting conditions, leaf conductance is primarily dependent on the level of irradiation (Stark, 1987), which varies form day to day. The greater degree of variation in the case of the drier treatments could be explained by the high frequency of small irrigation quantities. In especially the dry treatments, Pn declined gradually until irrigation, whereafter it recovered rapidly, contributing to the observed variation. Stomatal resistance showed the opposite response, which is in agreement with the results of Vos & Groenwold (1989). Similar daily oscillations of stomatal conductance as a result of changing weather conditions and frequent irrigations were reported by Vos & Groenwold (1989) in their drought studies.

Short-term measurements of physiological indices reflect the plant's reaction to water stress at the moment of observation, while tuber yield is a complex and integrated function of all processes throughout the plant life cycle. Mean values of physiological measurements, especially those collected during tuber bulking, should correlate better with tuber yield than incidental measurements (Shimshi *et al.*, 1983). Differences in Pn and Rs rates of different water treatments remained relatively stable over time in the present investigation, in spite of

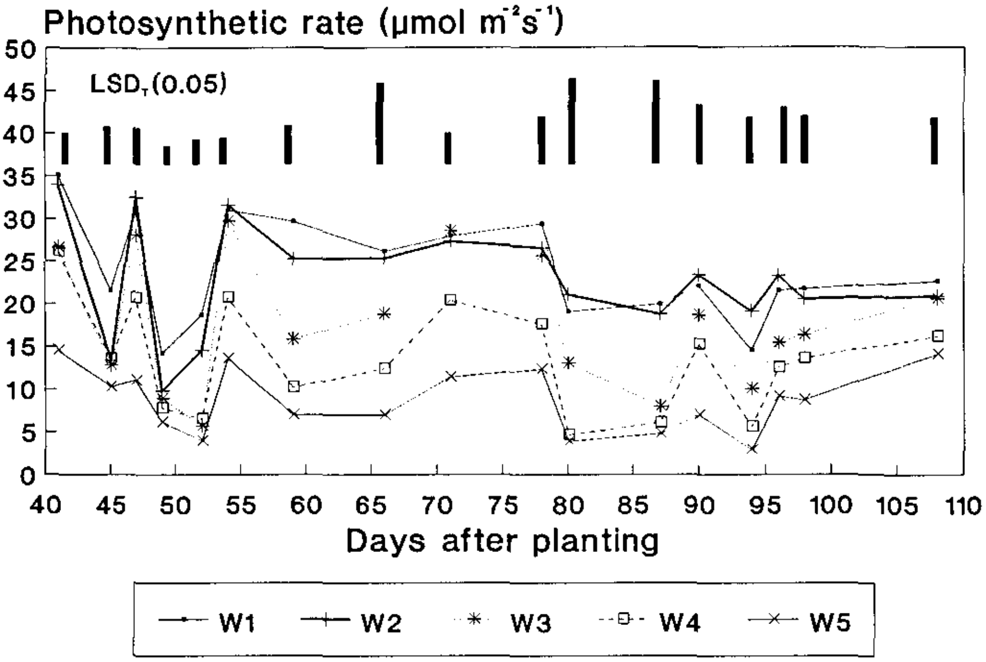


FIGURE 6.1: **Within-season variation of net photosynthetic rate of Late Harvest as influenced by five water regimes**

the observed daily variations. Therefore, seasonal mean values of photosynthetic rate and stomatal resistance for each genotype and water treatment were calculated. This method was also used by Schapendonk *et al.* (1989) and Shimshi *et al.* (1983) to enable the comparison of tuber yield with the physiological response of potato genotypes to stress.

The mean values of Pn and Rs of each genotype for the W1 treatment during the different seasons, are presented in Table 6.1. The values obtained are of the same order as those reported by Wolf (1993) for unstressed potato leaves. Fairly small genotypic differences in the average photosynthetic rate of unstressed plants were recorded in this study, although the genotypes Mnandi and 83-252-1 had lower values in spring, while Kimberley Choice and the two medium growing period cultivars had lower values in the autumn planting. This confirms that actual values of photosynthetic rate do not give any indication of the expected tuber yield, since Mnandi produced high yields for all the water treatments (Chapter 4).

TABLE 6.1 : Mean values of photosynthetic rate and stomatal resistance recorded for the well-watered treatment (W1) of each genotype during different plantings, as well as linear regression coefficients for the correlations between Pn, Rs and tuber yield

Genotype	Planting	Pn [1] (μmol m^{-2} s^{-1})	n [2]	SEM [3]	Regressions			Rs [4] (s cm^{-1})	n	SEM	a	b	r
					a	b	r						
Vanderplank	Autumn	20.47	17	1.85	-1.393	0.836	0.916	1.064	16	0.165	44.448	-8.167	-0.935
Buffelspoort	1992	22.81	17	1.73	-2.494	0.984	0.972	0.851	17	0.105	48.499	-6.801	-0.950
Up-to-date		18.82	17	1.64	1.088	1.065	0.999	1.355	17	0.208	57.957	-8.171	-0.999
BP1		18.74	17	2.39	-0.726	1.066	0.919	1.129	16	0.236	51.717	-6.872	-0.943
Kimberley Choice		18.80	17	2.10	0.447	0.912	0.998	1.440	16	0.244	47.83	-5.806	-0.994
Late Harvest		25.30	17	1.90	-1.284	0.760	0.991	0.775	16	0.090	45.062	-7.960	-0.976
Vanderplank	Spring	20.16	16	1.37	-4.615	2.444	0.985	1.590	16		58.885	-10.279	-0.982
Up-to-date	1992	23.73	18	1.66	-28.01	3.570	0.991	1.054	18		76.088	-19.539	-0.980
Late Harvest		23.70	18	1.38	-5.921	2.303	0.975	0.884	18		62.596	-14.582	-0.992
Late Harvest	Spring	22.00	8	1.77	4.760	2.044	0.941	0.870	8	0.171	52.718	-5.724	-0.970
Hoëvelder	1993	22.45	8	2.09	-4.413	2.903	0.971	1.065	8	0.276	68.501	-10.101	-0.984
Mnandi		17.82	8	1.41	-7.772	4.555	0.938	1.391	8	0.158	86.606	-11.809	-0.987
Up-to-date	Spring	24.51	6	1.97	15.295	2.272	0.866	1.018	6	0.271	76.097	-7.128	-0.921
82-252-5	1993	21.42	7	1.15	10.935	1.953	0.926	1.145	6	0.222	59.735	-6.732	-0.948
83-252-1		19.64	7	1.70	9.010	2.507	0.955	1.063	6	0.157	64.171	-7.195	-0.996

1 Pn = Net photosynthetic rate (μmol m^{-2}s^{-1})
2 n = number of observations
3 SEM = standard error of means
4 Rs = stomatal resistance (s cm^{-1})

Canopy size and shape may affect the relationship between photosynthetic rate and tuber yield: canopies intermediate in size and degree of upright growth habit appear to be the most efficient in terms of maximising tuber bulking rates (Lynch & Kozub, 1993). In the present study the size and shape of canopies were not recorded, but visual differences between genotypes were evident. These differences may have contributed to differences in the relationship between photosynthetic rate and tuber yield.

Regarding stomatal resistance, differences were observed in the mean Rs values recorded in the W1 treatment for the different genotypes (Table 6.1). Late Harvest (late cultivar standard) consistently had lower Rs values in the unstressed treatment (W1) than the other genotypes it was compared to in the same trial. The mean stomatal resistance of Up-to-date, the medium standard, remained fairly constant in the different trials (as was the case with Late Harvest), although it was slightly higher in autumn 1992.

Bansal & Nagarajan (1986), in an investigation of several physiological parameters as potential indices of drought resistance in potato genotypes, concluded that stomatal conductance is a better parameter than water saturation deficit and proline content. They found that the genotypes with the lowest stomatal conductance (i.e. highest resistance) for droughted treatments also showed the best drought tolerance. This does not seem to have been a consistent trend in the present trials: Late Harvest, for example, had the lowest stomatal resistance (or highest conductance) for the W5 treatment in the autumn 1992 trial (data not shown), but also appeared to be one of the more drought tolerant genotypes evaluated (Chapter 9). However, the severity of the drought stress imposed by Bansal & Nagarajan (1986) is questionable, as some genotypes in their study yielded almost 50% higher at the stressed treatment, compared to the unstressed treatment.

Linear regression was used to correlate seasonal mean photosynthetic rates and stomatal resistances of genotypes with their marketable yields (Table 6.1). Good correlations (r-values) were obtained for both parameters from all genotypes. These findings differ from those of Dwelle *et al.* (1981), who reported poor correlations between these parameters and tuber yield. The use of short-term measurements may be the reason for the poor correlations recorded in their study.

From Table 6.1 it is noteworthy that the slopes of regression between mean photosynthetic rate and tuber yield were always lower for Late Harvest than for the other genotypes in the same trial. This suggests that for Late Harvest tuber yield was less sensitive to reductions in photosynthetic rate than the other genotypes, which might be an indication of drought tolerance. However, this relation was not consistent for all genotypes: the calculated slopes of regression for Up-to-date, a drought sensitive genotype, were sometimes lower than those of more drought tolerant genotypes such as 83-252-1.

It is clear from these experiments that external factors other than water supply influence the relationship between mean photosynthetic rate, stomatal resistance and tuber yield, as both the intercepts and slopes of the regression functions changed with seasons. According to Dwelle (1985), characteristics such as canopy size and the distribution of assimilates may change as a result of factors such as temperature, thereby altering tuber yield. Jefferies & MacKerron (1993) have also demonstrated that the harvest index (distribution of assimilates) of some genotypes was reduced as a consequence of drought: Up-to-date, for instance, showed the greatest reduction in yield and had the lowest harvest index in the drought-stressed treatments. Decreased leaf expansion rates at temperatures above 25 °C, resulting in reduced leaf area indices, were observed by Bhagsari, Webb, Phatak & Jaworski (1988). They further observed that the availability of photosynthate for tuber development was reduced because canopy respiration rates increased two to three fold when temperatures rose from 25 °C to 35 °C.

From the preceding discussion it therefore appears that actual measurements of photosynthetic rate and stomatal resistance have little potential as aids in estimating tuber yield as affected by water supply, as their relationship to tuber yield is unique for each genotype and season, as well as for timing of measurements. As an alternative, the rates of reduction in photosynthesis and stomatal conductance in response to drought have previously been investigated as potential screening methods for drought tolerance in potatoes (Schapendonk *et al.*, 1989; Sukumaran *et al.*, 1989; Vos & Groenwold, 1989). These authors expressed the rates of photosynthesis and stomatal conductance recorded in water-stressed treatments relative to their values in an unstressed control. They concluded that genotypes that show greater reduction in rates of photosynthesis and stomatal conductance due to drought, are probably more drought sensitive.

The mean photosynthetic rates and stomatal resistances recorded for each genotype and water treatment in the present study are expressed relative to their values for the W1 treatment in Table 6.2. For the W2 treatment almost no decline in photosynthetic rate was observed for most of the genotypes (as was observed for tuber yield). For the other treatments (W3 - W5), marked reductions in photosynthetic rate and increase in stomatal resistance were observed for all genotypes.

Reductions in photosynthetic rate can generally be related to reductions in tuber yield, especially for the W3 and W4 treatments. Up-to-date is, however, an exception: during the spring plantings its yields generally declined more rapidly than its photosynthetic rate. The sensitivity of this genotype to high temperatures (Wolf *et al.*, 1989) probably aggravated the detrimental effects of water stress on its yield in spring. In a study by Leskovar *et al.* (1989) under similar conditions, it was found that despite Up-to-date's capacity to avoid short periods of water stress, it produced lower tuber yields than the other genotypes as a result of its sensitivity to high temperatures. High temperatures enhanced top growth at the expense of tuber growth in this cultivar. For some unknown reason, in the 1993 spring planting relative photosynthetic rates recorded for all genotypes in the W4 treatment of rain shelter #2 correlated poorly with relative yields.

Regression analysis on the data recorded for the W3, W4 and W5 treatments of all genotypes in all plantings indicates that relative photosynthetic rates are linearly related to relative tuber yields, as described by the following equation:

$$\textbf{Relative yield} = \textbf{0.0902 (SE 0.1551)} + \textbf{0.7696 (SE 0.1075)} \times \textbf{relative Pn} \qquad \textbf{(6.1)}$$

$$(\mathbf{r=0.758})$$

The exclusion of the Up-to-date data, and the data of the 1993 planting mentioned above,

TABLE 6.2 : Mean relative (expressed as fractions of values of the W1 treatment) photosynthetic rates, stomatal resistances and tuber yields, recorded for each genotype for five different water treatments

Genotype	Planting	W2			W3			W4			W5		
		Pn[1]	Rs[2]	Yield	Pn	Rs	Yield	Pn	Rs	Yield	Pn	Rs	Yield
Vanderplank	Autumn				1.017	1.086	0.722				0.380	3.845	0.273
Buffelspoort	1992				0.882	1.505	0.697				0.314	6.582	0.227
Up-to-date					0.761	1.940	0.792				0.308	3.780	0.342
BP1					0.973	1.417	0.711				0.392	4.677	0.328
Kimberley Choice					0.718	2.424	0.762				0.268	4.340	0.281
Late Harvest					0.747	2.390	0.655				0.373	5.240	0.339
Vanderplank	Spring	0.981	1.011	0.894	0.647	1.656	0.677	0.533	2.175	0.425	0.286	3.190	0.196
Up-to-date	1992	0.970	1.011	1.111	0.722	1.928	0.617	0.544	2.735	0.287	0.348	3.711	0.063
Late Harvest		1.002	1.350	0.983	0.751	2.030	0.808	0.559	2.576	0.591	0.360	4.070	0.207
Late Harvest	Spring	0.995	1.062	0.803	0.591	3.525	0.703	0.420	4.572	0.503	0.205	9.000	0.166
Hoëvelder	1993	0.980	0.949	0.858	0.615	2.510	0.598	0.401	3.918	0.441	0.267	5.741	0.107
Mnandi		0.828	1.609	0.975	0.561	2.578	0.712	0.505	2.982	0.521	0.351	4.521	0.181
Up-to-date	Spring	0.927	0.647	1.021	0.230	6.064	0.760	0.180	7.115	0.282	0.118	8.250	0.115
82-252-5	1993	0.975	0.882	0.870	0.507	3.519	0.637	0.189	5.099	0.486	0.188	5.640	0.165
83-252-1		0.921	1.260	0.895	0.413	3.847	0.628	0.251	5.098	0.427	0.187	7.007	0.174

[1] Pn = relative net photosynthetic rate

[2] Rs = relative stomatal resistance

improve the correlation coefficient substantially, and the regression function changes to the following:

$$\text{Relative yield} = 0.0309\ (\text{SE } 0.1124) + 0.8752\ (\text{SE } 0.0853) \times \text{relative Pn} \quad (r=0.879) \tag{6.2}$$

The linear relationship between relative photosynthetic rate and relative tuber yield indicates that for most of the genotypes evaluated in this trial, yield reduction as a result of drought might be predicted by a simple model (Equation 6.2) if the reduction in photosynthetic rate as a result of drought is known.

Good correlation coefficients were obtained for the linear relationship between relative stomatal resistance and relative tuber yield, but they were lower than the correlation coefficients obtained for photosynthetic rate. The following linear regression function for the data from the W3, W4 and W5 treatments of all genotypes represents the relationship between relative stomatal resistance and relative tuber yield:

$$\text{Relative yield} = 0.7552\ (\text{SE } 0.1839) - 0.0781\ (\text{SE } 0.0178) \times \text{relative Rs} \quad (r=-0.638) \tag{6.3}$$

Exclusion of the Up-to-date spring data, and the data for the 1993 spring planting, improves the regression coefficient and changes the regression function to:

$$\text{Relative yield} = 0.8328\ (\text{SE } 0.1378) - 0.1013\ (\text{SE } 0.0150) \times \text{relative Rs} \quad (r=-0.821) \tag{6.4}$$

The relationship between tuber yield reduction and increased stomatal resistance appears to be similar for all genotypes, as is the case with photosynthetic rate. This indicates that if the increase in stomatal resistance due to water stress is known, the expected yield reduction might be estimated with the aid of a simple regression model (Equation 6.4).

The effect of high temperatures on the distribution of assimilates is not accounted for by these models. A heat-sensitive genotype may therefore produce lower tuber yields than predicted from its relative stomatal resistance or photosynthetic rate. Obviously, numerous processes are involved in the adaptation to drought, and simple direct relationships between drought tolerance and ultimate tuber yield can not be established.

6.4 Conclusions

Photosynthetic rate (Pn) and stomatal resistance (Rs) are potentially useful predictors of drought tolerance in potato genotypes, since the relationship between relative values of these indices and relative tuber yields appears to be consistent. Actual measurements of either of these parameters are not useful for estimating tuber yield, although correlations with tuber yield were good. This is attributable to the fact that the relationship between Pn or Rs and tuber yield is affected by factors (e.g. temperature) which may influence aspects such as canopy development and harvest index.

Simple regression models are suggested for the estimation of expected reductions in tuber yield from the reductions in measured rates of Pn or Rs resulting from drought stress. Although these empirical models did not account for actual yield reductions under all circumstances, they still appear to be useful for selection of drought tolerance: all genotypes which showed great reductions in photosynthetic rate (or increases in stomatal resistance) as a result of drought, were prone to yield reduction in the current study. The limited number of genotypes for which these physiological measurements were recorded, did not differ substantially in their ability to tolerate drought (see Chapter 9), except for the cultivar Up-to-date, which is drought (and heat) sensitive. Consequently, large differences in relative photosynthetic rates, stomatal resistances and tuber yields were not obvious.

In conclusion, the use of relative photosynthetic rate and stomatal resistance as indices of drought tolerance in potato genotypes is promising, but further investigation on a wider range of more diverse genotypes is needed.

CHAPTER 7

THE EFFECT OF WATER REGIMES ON WATER-USE CHARACTERISTICS OF POTATO GENOTYPES

7.1 Introduction

Potatoes require a relatively high level of soil water for optimum yield and quality (Miller & Martin, 1987b). The sensitivity of the crop to even short periods of mild water stress has been demonstrated in many research projects (Van Loon, 1981; Dwelle, 1985; Van Loon, 1986). The effects of water stress on tuber yield and quality depend on the timing and severity of the stress. Tuber number is limited by water stress during the tuber initiation phase, while the rate of tuber growth is reduced by water stress in the bulking phase. Total yield is thus primarily harmed by drought between tuber initiation and maturity (Miller & Martin, 1987b). Interruption in water supply may influence tuber quality at almost any growth stage after tuber initiation (Mould & Rutherfoord, 1980; Ojala *et al.*, 1990; Jefferies & MacKerron, 1993; Shock *et al.*, 1993).

Most published water-use data for potato crops have been recorded in temperate climates (Doorenbos & Kassam, 1979). In tropical and subtropical climates the high evaporative demand increases crop water requirements, which may compound the sensitivity to water stress, resulting in greater yield reductions than those expected from similar water deficits under cooler conditions (Trebejo & Midmore, 1990). According to Doorenbos & Kassam (1979), the seasonal water requirement of potato crops varies between 500 and 700 mm and water-use efficiencies range between 40 and 70 kg ha^{-1} mm^{-1} for a 120- to 150-day crop, depending on the season. In the subtropical climate of Peru, Trebejo & Midmore (1990) recorded mean water-use efficiencies of 39 kg ha^{-1} mm^{-1} and 124 kg ha^{-1} mm^{-1} for hot and cool seasons, respectively. They recorded higher yield losses and lower water-use efficiencies in hot seasons, mainly because of the greater saturation vapour pressure deficit in hot seasons.

Droughted plots showed the highest water-use efficiencies due to greater harvest index values and more efficient interception of solar radiation per unit water applied. Lower harvest indices in summer were to some extent responsible for seasonal differences in water-use efficiencies.

Little is known about the water requirements of potatoes in the southern African subtropical climate. The water requirements of potato crops do presumably also depend on the season, as potatoes may be cultivated at different times of the year for some localities. The yield response of different potato genotypes was discussed in Chapter 4. In this chapter the specific water requirements of locally cultivated genotypes in different environments will be investigated.

7.2 Materials and methods

Studies to determine the water requirements and the effects of different levels of water stress on the production of different potato genotypes were carried out over a period of four years. The details of cultivation practices and treatments applied in the three spring and four autumn plantings are fully described in Chapters 2 and 3.

An irrigation boom system was used to induce five levels of water stress. Soil-water content of all the plots was determined three times per week at 150-mm intervals to a depth of 1200 mm using a neutron probe (DR 503). On some occasions the measuring depth was only down to 600 mm. The irrigation amount was calculated according to the soil-water deficit in the 0 - 600-mm zone. Irrigation scheduling was based on the soil-water content of the W1 treatment and the profile was refilled by irrigation whenever there was a 20% depletion of the total amount of water held by the root zone at field capacity. The other four treatments were irrigated on the same day, but on average received 82, 56, 46 and 28 percent, respectively of the amount applied to W1. The soil-water deficit was calculated as follows for each of the 300-mm zones:

$$\mathbf{D_i = (FC_i - WC_i) \times \rho b_i \times d_i} \qquad \mathbf{(7.1)}$$

where D_i = soil-water deficit (mm) in soil layer i, FC_i = gravimetric field capacity (%) of soil layer i, WC_i = gravimetric soil-water content (%) of soil layer i, b_i = bulk density (g cm^{-3}) of soil layer i, and d_i = depth of soil layer i (m). The change in soil-water content (dW) between two measurement dates was calculated as:

$$\mathbf{dW = D_0 - D_i} \tag{7.2}$$

where D_0 and D_i = soil-water deficits on days 0 and i, respectively. The evapo-transpiration (ET) was calculated as:

$$\mathbf{ET = dW + I} \tag{7.3}$$

where I = amount of irrigation (mm), assuming that run-off and drainage were zero. Total water use (WU) at the end of the season was calculated as:

$$\mathbf{WU = D_E - D_0 + I} \tag{7.4}$$

where D_E and D_0 are the soil-water deficits at the end and start of the growing season, respectively.

Tuber yield and tuber-size distribution results are reported and discussed in Chapter 4. In this chapter the total amounts of water used by the various genotypes for the different water treatments are presented. Water-use efficiencies and production functions of the different genotypes are also discussed.

7.3 Results and discussion

The total amount of water used by the different genotypes subjected to the wet treatments (W1) ranged from 215 mm in the 1995 autumn to 820 mm in the 1994 spring planting (Tables 7.1 and 7.2).

TABLE 7.1 : Total Class A-pan evaporation and water use (mm) of potato genotypes exposed to five water treatments during spring plantings

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water use (mm) per water treatment				
				W1	W2	W3	W4	W5
Spring	Vanderplank	1	1046	453	409	331	273	240
1992	Up-to-date	1		545	493	406	326	275
	Late Harvest	1		554	495	405	328	269
	Vanderplank	2		663	580	499	377	299
	Up-to-date	2		708	675	574	427	326
	Late Harvest	2		709	672	585	426	335
Spring	Late Harvest	1	947	654	531	395	338	235
1993	Hoëvelder	1		655	535	397	334	222
	Mnandi	1		650	516	382	328	226
	Up-to-date	2		613	530	409	344	254
	82-252-5	2		616	529	413	347	242
	83-252-1	2		621	504	396	349	252
Spring	Late Harvest	1	1070	817	627	463	384	285
1994	81-163-40	1		820	631	469	385	293
	83-363-67	1		799	611	459	388	266
	Up-to-date	2		813	652	492	405	259
	Mondial	2		806	657	477	377	271
	84-304-4	2		340	252	217	182	139

TABLE 7.2 : **Total Class A-pan evaporation and water use (mm) of potato genotypes exposed to five water treatments during autumn plantings**

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water use (mm) per water treatment				
				W1	W2	W3	W4	W5
Autumn 1992	Vanderplank	1 & 2	612	346	207	192	175	116
	Buffelspoort	1 & 2		344	287	201	174	115
	Up-to-date	1 & 2		344	273	191	169	110
	BP1	1 & 2		354	276	204	175	122
	Kimberley Choice	1 & 2		358	292	198	174	130
	Late Harvest	1 & 2		355	279	210	171	125
Autumn 1993	Vanderplank	1	528	277	256	208	170	137
	Up-to-date	1		282	261	211	171	136
	Late Harvest	1		274	254	201	164	131
	Vanderplank	2		494	441	352	281	228
	Up-to-date	2		495	445	362	288	236
	Late Harvest	2		492	439	356	283	230
Autumn 1994	Late Harvest	1	562	554	390	296	233	174
	Hoëvelder	1		558	391	303	235	179
	Mnandi	1		589	400	296	233	170
	Up-to-date	2		577	436	312	270	205
	82-252-5	2		557	437	323	293	199
	83-252-1	2		554	436	306	280	188
Autumn 1995	Late Harvest	1	478	222	206	174	168	148
	81-163-40	1		217	202	174	166	141
	83-363-67	1		215	200	179	168	149
	Up-to-date	2		282	234	187	170	145
	Mondial	2		265	228	192	186	147
	84-304-4	2		219	202	145	131	94

Genotypes showed small differences in total seasonal water use within the same trial and for the same water treatment. Vanderplank, an early cultivar, used less water than the other genotypes in the same trial during spring. The genotype 84-304-4 used the least water in both spring and autumn plantings, because of *Erwinia* disease (spring 1994) and plant population problems (autumn 1995) encountered. Total water use was a function of the amount of water applied, and genotypes of the same maturity class used approximately the same amount of water. Throughout the study there was little evidence of genotypes tending to deplete the soil water at different rates (see Figures 7.1 and 7.2 as examples). As genotypes in the same trial received the same amount of water, differences in water use can only be explained by differences in initial soil-water content and by the degree of soil-water depletion at the end of the season (equation 7.4). Deep percolation (not accounted for) might also have occurred for some of the genotypes since the mean deficit of the W1 regime of all genotypes was used to calculate irrigation amounts. It therefore seems that, although the irrigation boom method is suitable for drought-screening purposes, application of the same amounts of water to all genotypes and the limited number of water regimes offered, may be of the biggest disadvantages of the irrigation boom in determining the water requirements of crops.

The reason for lower water use of the same genotypes in rain shelter #1, compared to rain shelter #2 for the 1993 autumn planting is not clear. The lower total water use and total yields obtained in the wet treatment of rain shelter #1 may indicate that the plants were exposed to water stress, probably due to incorrect irrigation scheduling.

As the level of soil-water depletion from the different soil layers showed similar seasonal trends, the graphs of only one season are presented as examples (Figures 7.1 to 7.4). No significant genotypic differences were evident in any of the soil layers: the soil zones of highest root activity, the shallower zones, showed the highest degree of depletion with only a small portion of the total water used from soil layers below 900 mm.

Water use of the same genotypes in spring plantings was between 12 % (spring 1993 versus autumn 1994) and 210% (spring 1994 versus autumn 1995) higher than in autumn. This is partly attributable to the shorter autumn season, but also to the high atmospheric evaporative

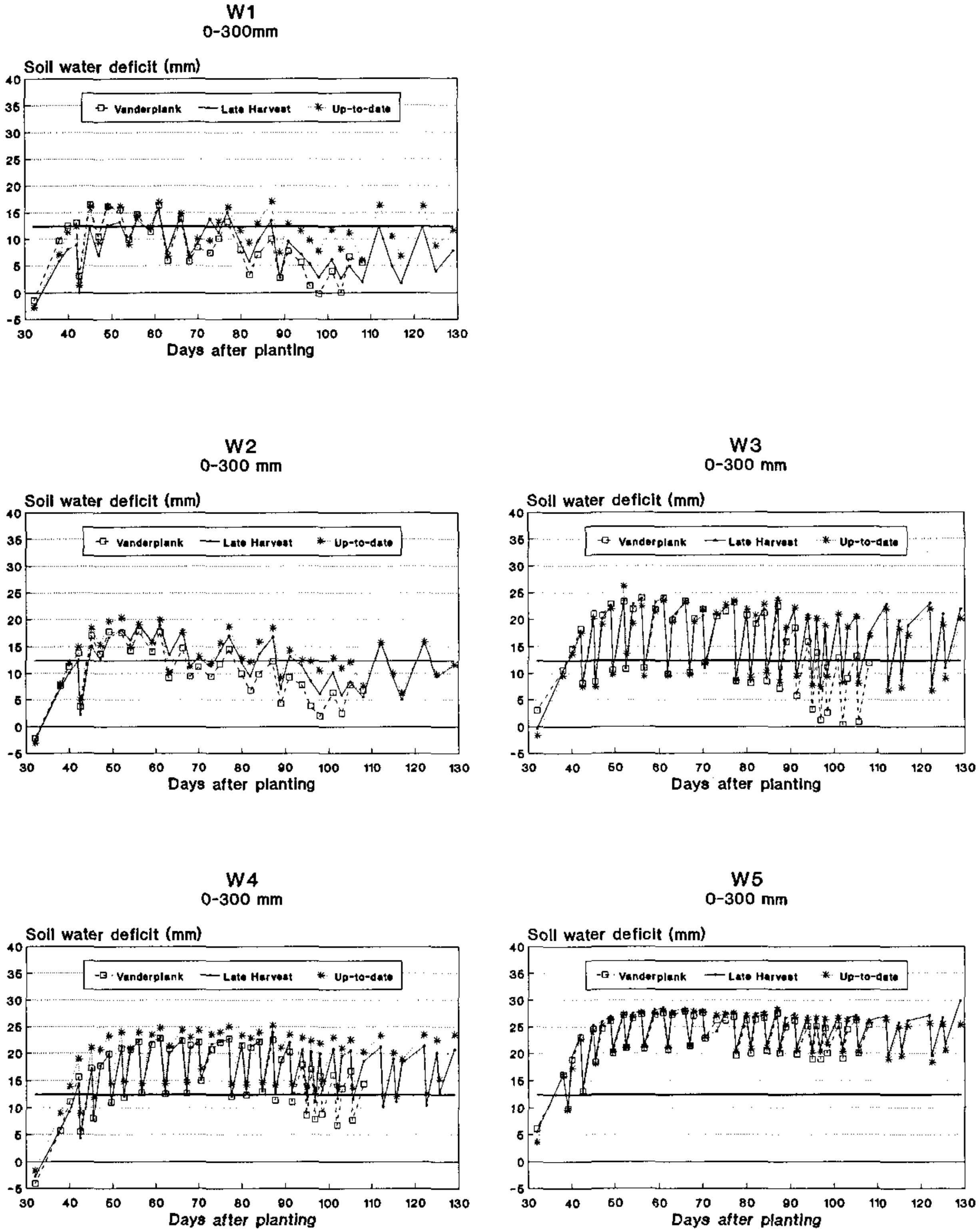


FIGURE 7.1 : Seasonal variation of soil-water deficits in the 0 to 300-mm soil zone for three genotypes at five water treatments (W1 - W5). Solid horizontal line represents 20% depletion of total soil water

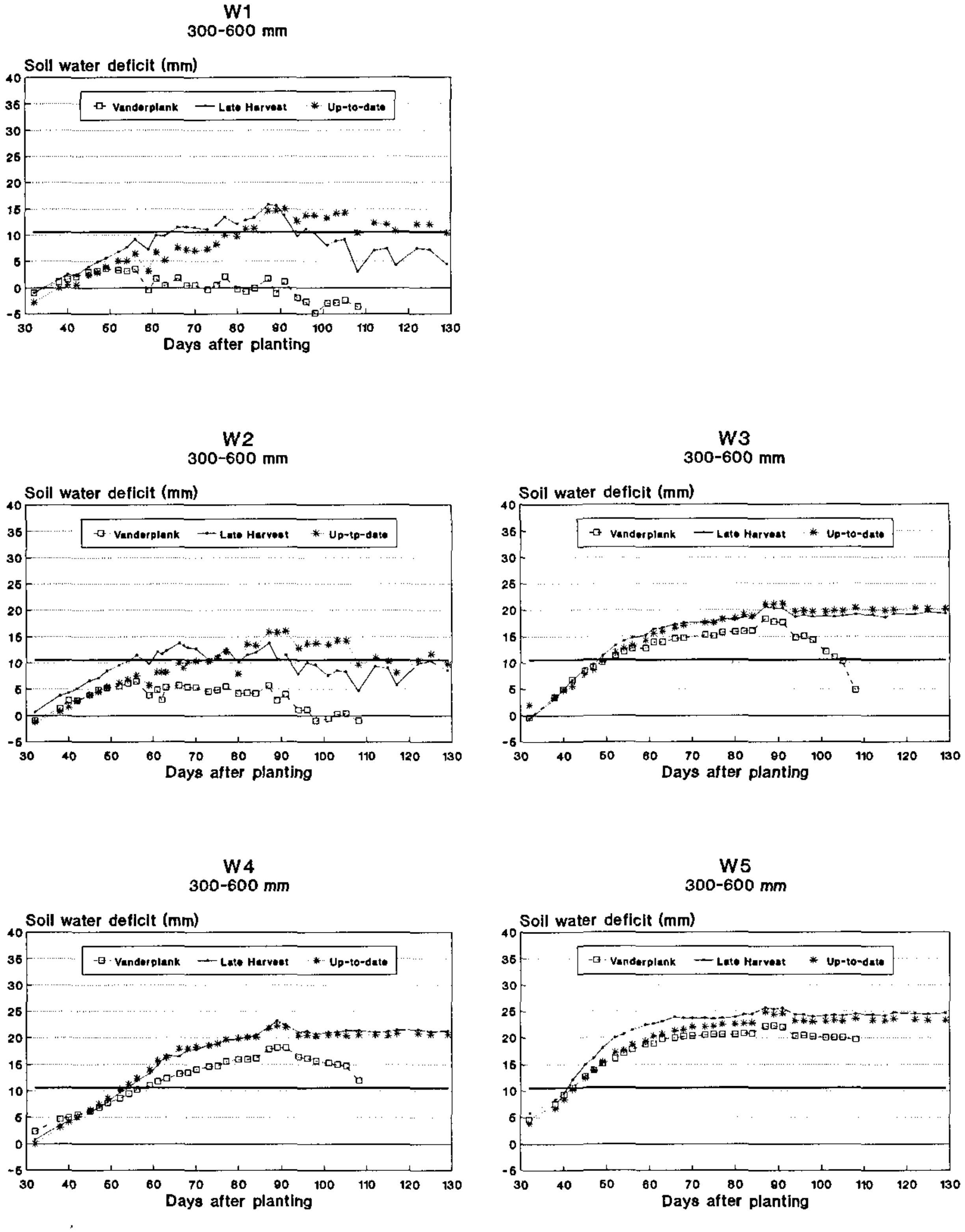


FIGURE 7.2 : Seasonal variation of soil-water deficits in the 300 to 600-mm soil zone for three genotypes at five water treatments (W1 - W5). Solid horizontal line represents 20% depletion of total soil water

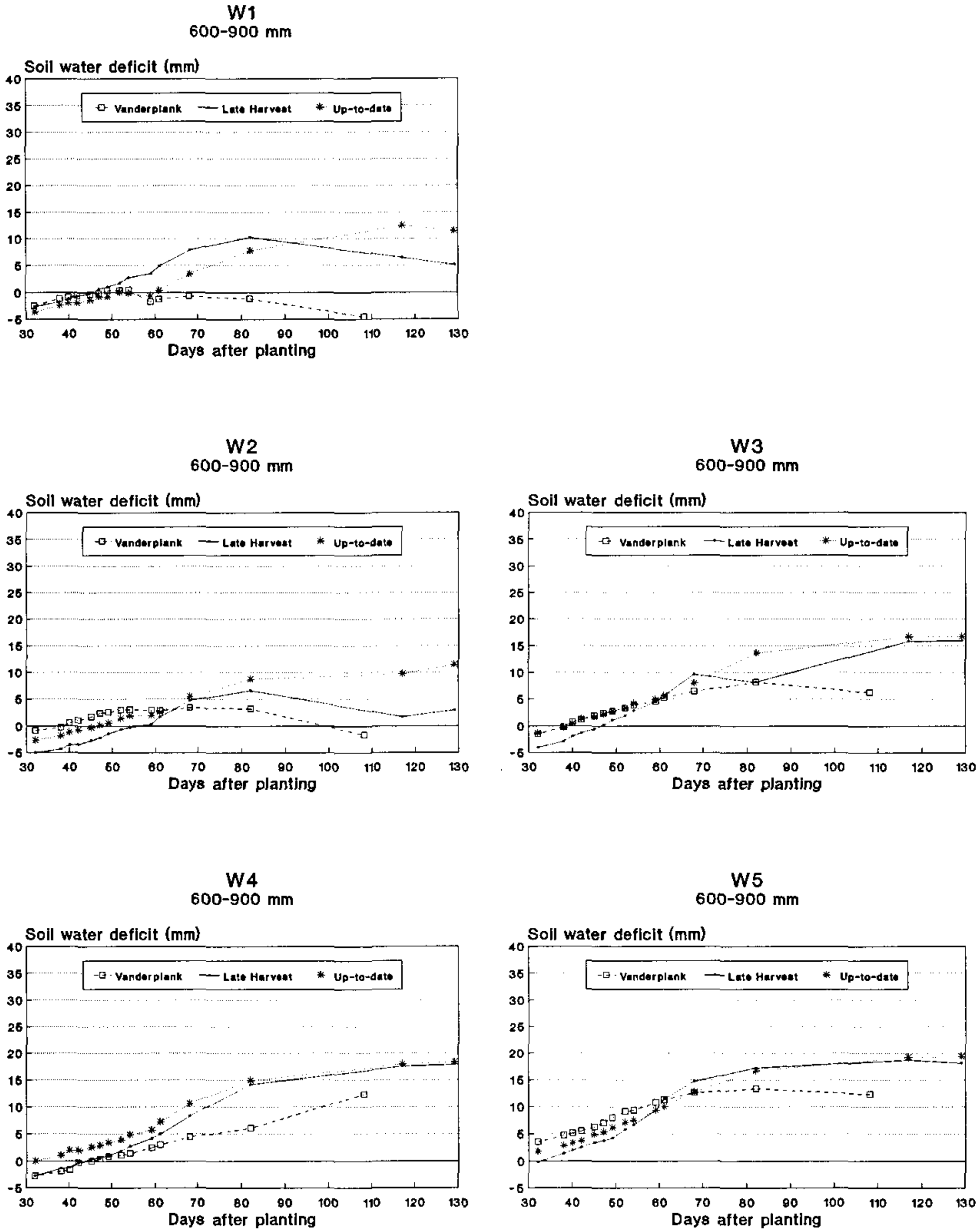


FIGURE 7.3 : Seasonal variation of soil-water deficits in the 600 to 900-mm soil zone for three genotypes at five water treatments (W1 - W5)

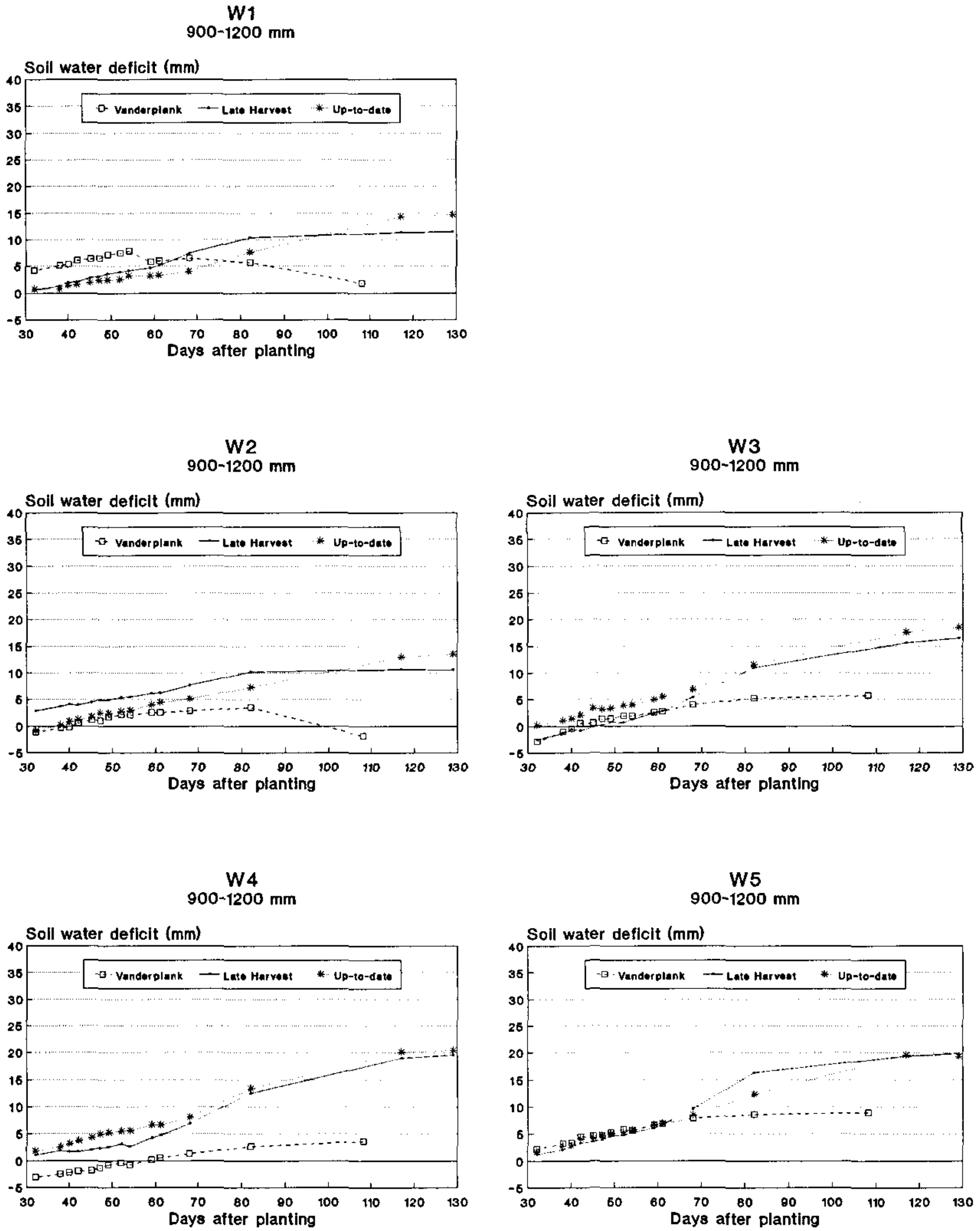


FIGURE 7.4 : Seasonal variation of soil-water deficits in the 900 to 1200-mm soil zone for three genotypes at five water treatments (W1 - W5)

demand in the spring plantings (see Tables 7.1 & 7.2 and Figure 3.1). Tanner (1981) suggested the normalising of transpiration (T) for seasonal vapour pressure deficit (e*- e) to make transpiration data of different seasons more comparable. For a given crop the following relationship then becomes true:

$$\mathbf{Y/T = k / (e^{*} - e)} \tag{7.5}$$

or

$$\mathbf{Y/k = T / (e^{*} - e)} \tag{7.6}$$

where Y is the total dry matter produced in mass per area; T is the seasonal transpiration; k is constant for a specific crop and canopy; and (e*- e) is the daytime saturation vapour pressure deficit of the air, assuming that leaf temperature is equal to air temperature.

Normalised seasonal values of T/(e*- e) can be calculated in various ways. The best method is to derive an integrated value for the growing period from accumulated values of daily normalised evapotranspiration measured with a lysimeter. A second method, which usually gives an underestimate of k (Tanner, 1981), is to divide the mean seasonal transpiration by the mean seasonal daytime vapour pressure deficit.

The value of daily normalised transpiration will depend on how (e*- e) is calculated. Using an integral for the daytime transpiration period, i.e. the mean of hourly (e*- e) for the transpiration period, gives the best estimate of daily (e*- e). When hourly data is not available, daily normalised transpiration can be calculated using the mean of (e*- e) at minimum and maximum temperatures.

As it was not possible in this study to measure transpiration separately, evapotranspiration data (total water use) were normalised. Since complete weather data sets were available only for the period autumn 1993 to autumn 1995, the water-use data prior to that could not be normalised. Daily (e*- e) was calculated as the mean of (e*- e) at minimum and maximum temperatures, as some of the data sets lacked hourly temperatures. Normalised seasonal evapotranspiration values for the W1 treatments of the autumn 1993 to autumn 1995 plantings were used in the calculation of water-use efficiencies normalised for vapour pressure deficit.

Water-use efficiencies obtained for the different plantings are shown in Tables 7.3 and 7.4. Generally, water-use efficiencies were higher in autumn (mean 127 kg ha^{-1} mm^{-1}) than in spring plantings (mean 94 kg ha^{-1} mm^{-1}) for most of the genotypes. This trend is in agreement with those reported for other studies conducted in subtropical climates (Trebejo & Midmore, 1990). The lower water-use efficiencies recorded in summer are most probably due to greater soil evaporation and lower transpirational water-use efficiencies. Mean water-use efficiencies calculated for autumn plantings in the W1 treatments over all the years and genotypes were much higher than those recorded by Trebejo & Midmore (1990) for the same time of year (their summer trials): 127 kg ha^{-1} mm^{-1} water applied on fresh tuber mass basis versus 44.3 kg ha^{-1} mm^{-1} recorded for their unstressed treatments. The water-use efficiencies recorded by them in winter were similar to those recorded in this study in autumn: 122 kg ha^{-1} mm^{-1} versus 127 kg ha^{-1} mm^{-1}. The lower water-use efficiencies recorded by Trebejo & Midmore (1990) in summer are possibly due to the higher temperatures and higher atmospheric evaporative demand recorded for their locality.

Highest water-use efficiencies were in most instances recorded for the intermediate water regimes: in spring plantings the highest water-use efficiency values were recorded for the W2 and W3 treatments for all the genotypes, with the exception of Vanderplank during the 1992 spring planting, when the highest value was recorded for W4. In the autumn plantings most of the highest water-use efficiencies were also recorded in W2 and W3, but in 1993 and 1994 the highest water-use efficiencies were recorded in W4 for some of the genotypes. The highest water-use efficiencies were recorded at the W1 treatment for some genotypes during the cool 1995 autumn.

It was difficult to compare genotypic water-use efficiencies over different years because of year effects. Genotypes were therefore evaluated according to their water-use efficiencies within the same maturity class and season. During the 1992 spring planting either Late

TABLE 7.3: Water-use efficiencies (kg ha^{-1} mm^{-1}) of potato genotypes exposed to five water treatments during spring plantings

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water use (mm)				
				W1	W2	W3	W4	W5
Spring 1992	Vanderplank	1	1046	107.7	108.9	102.3	78.0	47.9
	Up-to-date	1		89.4	96.7	97.7	89.1	40.8
	Late Harvest	1		100.0	102.3	104.4	55.0	17.1
	Vanderplank	2		73.3	80.0	88.2	91.7	59.0
	Up-to-date	2		79.5	81.8	81.2	76.9	41.1
	Late Harvest	2		91.4	99.7	95.3	73.1	32.9
Spring 1993	Late Harvest	1	947	86.2	85.4	104.2	91.3	57.0
	Hoëvelder	1		101.4	110.2	109.8	96.4	49.7
	Mnandi	1		110.6	132.5	135.4	122.1	74.1
	Up-to-date	2		116.8	140.6	140.0	63.4	45.4
	82-252-5	2		93.9	99.0	94.6	88.5	49.5
	83-252-1	2		98.1	108.3	98.1	81.4	52.7
Spring 1994	Late Harvest	1	1070	64.4	86.0	102.4	99.7	59.7
	81-163-40	1		73.8	82.7	106.8	86.2	16.7
	83-363-67	1		81.4	102.0	109.2	99.2	49.2
	Up-to-date	2		99.4	103.8	100.2	82.4	41.3
	Mondial	2		90.5	100.4	97.6	70.6	37.6
	84-304-4	2		136.3	160.9	162.4	120.1	67.3

TABLE 7.4 : **Water-use efficiencies (kg ha^{-1} mm $^{-1}$) of potato genotypes exposed to five water treatments during autumn plantings**

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water-use efficiencies (kg ha^{-1} mm $^{-1}$)				
				W1	W2	W3	W4	W5
Autumn 1992	Vanderplank	1 & 2	612	118.6	206.8	156.3	117.1	96.6
	Buffelspoort	1 & 2		140.4	161.8	167.4	123.9	95.8
	Up-to-date	1 & 2		135.0	171.0	193.2	160.4	145.1
	BP1	1 & 2		138.7	179.8	171.1	163.2	131.9
	Kimberley Choice	1 & 2		107.4	126.3	148.0	112.0	83.3
	Late Harvest	1 & 2		115.9	139.5	128.4	131.8	111.5
Autumn 1993	Vanderplank	1	528	150.3	159.5	117.1	105.3	37.8
	Up-to-date	1		198.2	206.7	221.6	212.1	156.1
	Late Harvest	1		206.6	206.0	217.8	218.3	163.3
	Vanderplank	2		62.2	69.0	92.5	102.7	93.2
	Up-to-date	2		105.9	112.9	127.2	122.4	115.1
	Late Harvest	2		121.1	133.4	136.7	146.5	134.7
Autumn 1994	Late Harvest	1	562	105.2	121.9	146.1	125.7	114.9
	Hoëvelder	1		104.2	119.2	127.1	120.9	110.3
	Mnandi	1		115.8	128.2	149.6	134.6	113.1
	Up-to-date	2		92.9	110.6	151.8	160.2	144.3
	82-252-5	2		97.3	114.6	168.9	159.0	137.3
	83-252-1	2		87.9	103.1	153.1	159.0	129.3
Autumn 1995	Late Harvest	1	478	144.7	134.1	129.5	125.4	120.7
	81-163-40	1		180.4	154.5	160.1	148.7	144.3
	83-363-67	1		146.1	128.5	125.0	124.7	93.4
	Up-to-date	2		104.6	108.3	108.8	106.6	127.6
	Mondial	2		161.9	168.3	158.4	136.5	149.0
	84-304-4	2		115.5	126.5	139.5	127.5	151.7

TABLE 7.5 : Water-use efficiencies of potato genotypes normalised for seasonal vapour pressure dificit (kg $\text{ha}^{-1}\,\text{mm}^{-1}\,\text{kPa}^{-1}$) for the W1 regime during spring and autumn plantings

Genotype	Rain shelter #	A-pan evaporation (mm) in spring	A-pan evaporation (mm) in autumn	Normalised water use efficiency	
				Spring	Autumn
Vanderplank	1	1046	528		161.6
Up-to-date	1				213.2
Late Harvest	1				222.2
Vanderplank	2				66.9
Up-to-date	2				113.9
Late Harvest	2				130.1
Late Harvest	1	947	562	101.8	120.9
Hoëvelder	1			119.8	119.8
Mnandi	1			130.6	133.0
Up-to-date	2			137.9	106.8
82-252-5	2			110.9	112.5
83-252-1	2			115.9	101.0
Late Harvest	1	1070	478	88.4	124.0
81-163-40	1			101.3	154.6
83-363-67	1			111.7	125.2
Up-to-date	2			136.4	89.6
Mondial	2			124.2	138.7
84-304-4	2			187.1	99.0

Harvest or Vanderplank had the best water-use efficiencies for all the water regimes with Vanderplank doing especially well under dry conditions (W4 and W5). Mnandi had the highest water-use efficiency among the late genotypes for all water treatments during the 1994 spring planting, while Up-to-date performed best only in the wetter (W1 - W3) treatments. Among the late genotypes, 83-363-67 had the highest water-use efficiencies for all regimes (except W5) during 1994. If genotype 84-304-4 is excluded from the data (because of its early death resulting from *Erwinia* disease), Up-to-date was the medium genotype with the highest water-use efficiencies in the 1994 spring planting.

During the autumn plantings there was little change in the ranking of genotypes over water treatments within the same year: in the 1992 planting BP1 and Up-to-date had the highest water-use efficiencies throughout all treatments, while in 1993 Late Harvest had the highest water-use efficiency, followed by Up-to-date. Mnandi had the highest water-use efficiencies during both the 1993 spring and 1994 autumn plantings. The genotype 82-252-5 was the medium grower with the highest water-use efficiency during the 1994 autumn. Mondial and 81-163-40 had the highest water-use efficiencies in all water treatments during 1995.

Since the assumption that air and leaf temperatures are equal is not valid for stressed plants, where leaf temperatures are sometimes higher than air temperatures, water-use data were normalised for the unstressed W1 treatments only. When normalised water-use data are used in the calculation of water-use efficiency, the water-use efficiency values for the same genotypes in different years are closer to each other: normalised water-use efficiencies for Late Harvest in the different autumn seasons were 130.1, 120.9 and 124 kg ha^{-1} mm^{-1} kPa^{-1} respectively, compared to values of 150.3, 105.2 and 144.7 kg ha^{-1} mm^{-1} before normalising (Tables 7.3 to 7.5). Some variation was, however, still evident. Firstly, in the autumn of 1993, the water-use efficiencies of rain shelter #1 were very high compared to rain shelter #2. The substantially lower yields recorded for the W1 treatment of rain shelter #1 do, however, suggest that these plants were probably stressed in the specific season, as discussed earlier in this section. Secondly, water-use efficiencies for the same genotypes were higher in autumn than spring plantings, probably due to the difference in length between the two growing seasons: spring (summer) seasons are approximately 120 to 130 days long, while autumn seasons are 75 to 80 days in length. The use of evapotranspiration instead of transpiration (as suggested by Tanner, 1981) in the calculation of water-use efficiency may be a further source for the differences encountered between seasons: in spring plantings more water is lost through evaporation without contributing to dry matter production compared to autumn.

7.4 Conclusions

The total water use of the different genotypes was similar for the same trial, possibly because water use is calculated primarily as a function of the amount of water applied. Since genotypes of the same maturity class receive the same amount of water, differences in water use can only be due to differences in initial and final soil-water contents. These differences in soil-water content were generally small, leading to small genotypic differences in calculated total water use. It is not known whether the calculated water use of genotypes would have been different if they were irrigated individually. If their water requirements would differ, the objective of this study to determine the water requirements of different genotypes may therefore not be achieved and it should be concluded that the irrigation boom method may therefore not be ideal for determining crop-water requirements of a mixture of genotypes or species, although it is useful for drought tolerance screenings.

The results obtained from this study thus provide no evidence that genotypes of the same maturity class have different water requirements and it is therefore assumed that the same crop parameters would apply for all genotypes in an irrigation scheduling model (Chapter 10).

Generally, little water was depleted below the 900- mm soil layer, regardless of genotype and water regime applied. Taking into account the small fraction of the total water use depleted below 600 mm, it is suggested that this depth be considered the maximum rooting depth for irrigation scheduling calculations. Further, the rate of depletion from the different soil layers did not differ for any of the genotypes within the same season.

The highest water-use efficiencies were, with few exceptions, recorded for the intermediate water treatments (W2 - W3). These regimes also offered the best compromise between highest yield and tuber quality, and are therefore recommended as the most beneficial. Water-use efficiencies were higher in autumn than in spring plantings, probably due to larger vapour pressure deficits and a greater evaporation component during spring, leading to more water being lost without contributing to the production of dry matter. Therefore, in production areas that offer the possibility of two planting seasons, potatoes should preferably be cultivated in autumn to ensure the highest yield per unit water applied if irrigation water is limited.

In spring plantings, the genotypes classified as drought-tolerant in Chapter 9 (Late Harvest, Mnandi, 83-363-67 and Vanderplank) generally had the highest water-use efficiencies. In some plantings, Up-to-date had the highest water-use efficiencies among the medium genotypes, but this was usually only the case for the wetter treatments (W1 - W2).

The same genotypes had the highest water-use efficiencies in all water regimes for the same trial during autumn: Late Harvest, Mnandi and 81-163-40 among the late-maturity class and BP1, Up-to-date, Mondial and 82-252-5 among the medium maturity class.

Water-use efficiencies calculated from seasonal water use, normalised for vapour pressure deficit, were similar for the same genotype and planting (spring or autumn) over different years. The differences still evident between plantings could probably be reduced by using seasonal transpiration instead of evapotranspiration to calculate water-use efficiency.

CHAPTER 8

THE INFLUENCE OF WATER REGIMES ON ROOT GROWTH

8.1 Introduction

The potato plant is known to have a shallow and poorly distributed root system, compared to crops like wheat and maize (Fulton, 1970). Shallow root systems reduce the volume of soil from which roots can extract water and nutrients (Miller & Martin, 1990; Incerti & O'Leary, 1990). Adequate soil water is required to ensure satisfactory yield and quality of potato tubers (Miller & Martin, 1990).

Root systems of actively growing plants continually explore new regions of soil. The most rapid water absorption is considered to occur from the zones of maximum rooting density near the soil surface (Fulton, 1970). When these layers dry out while deeper soil layers are still wet, the zone of maximum absorption then moves downward and outward. Water will mainly be absorbed from wet soil, until most available water from the root zone is depleted. Deep-rooted crops should therefore be able to extract water from larger soil volumes than shallow-rooted crops (Fulton, 1970).

The stimulation of deeper root systems by drought has been reported in the literature for many crops. Within the same species deeper root systems hold promise of better drought tolerance, presumably by being able to withdraw water from deeper zones between irrigations, which enables the plant to maintain its physiological processes. Ekanayake & Midmore (1992), using root-pulling resistance in combination with high yielding ability under water deficit conditions to classify the drought tolerance of potato genotypes, found a significant correlation ($r=0.569^{***}$) between tuber yield and root-pulling resistance under conditions of moderate drought. This suggests that the pulling-resistance method can help in the selection of high-yielding, drought-resistant potato genotypes adapted to the tropics. Studies by Stalham & Allen

(1993) have shown that Cara, an indeterminate cultivar, has a deeper and more ramified root system than Desirè, and was able to utilise water from deeper soil zones, which enabled it to survive longer and produce higher yields than Desirè. The work of Jefferies & MacKerron (1993), however, has indicated that there was little difference in drought tolerance between these two cultivars. Local studies with the cultivar Up-to-date (unpublished data) have indicated that although drought resulted in slightly deeper root development, the majority of roots (>85%) occurred in the upper 600 mm soil layer. It therefore appears that, at least in this case, adaptation to water stress by the development of deeper roots was limited.

Root studies on potatoes are limited, as they are time consuming, tedious and often subjective (Harris & Campbell, 1989). Stimulated by promising results reported in the literature (Ekanayake & Midmore, 1992; Stalham, 1993), the present studies included the rooting response of various potato genotypes to different water regimes over a period of three years. The hypothesis was that genotypes that are able to develop deeper root systems in order to extract water from deeper soil layers will be more drought tolerant. If this proved to be true, such a trait might be a useful tool for selection in breeding programmes.

8.2 Materials and methods

Root data were collected from the 1993 spring until the 1995 autumn planting. Details of cultivation practices and water treatments applied are described in Chapters 3 and 4. As plots were small, measurements were limited to one sampling per season in order to reduce disturbance of the plants and soil profile. Sampling took place at the start of foliage senescence on one replication per trial, and only for the W1, W3 and W5 water treatments.

A steel sampling tube with hardened cutting tips (42 mm in diameter) was used to obtain the soil cores down to a soil depth of 1200 mm, similar to the method used by Incerti & O'Leary (1990) and Box & Ramseur (1993). Three cores from each plot were taken: two in the row 150 mm from the base of a plant, and one from the midpoint between two adjacent rows. The soil cores were divided into 300 mm segments and the three segments from corresponding depths were combined. These were sealed in plastic bags and stored in a deep freezer. Each sample was later washed over a 400 micron screen, using a specially designed cyclone water washer. Roots were collected and stored in phenoxy indole acetic acid (FAA), whereafter they were oven-dried at 50 °C for two days. Total length per root sample was measured by the line intersection method (Leskovar *et al.*, 1989; Chan & Mead, 1992), which is widely used because of its simplicity and accuracy (Harris & Campbell, 1989). Root concentrations were expressed as root length densities in units of km m^{-3}.

8.3 Results and discussion

Results of root length densities recorded for the various plantings are presented in Figures 8.1 to 8.6. No statistical analysis was conducted on the data as root samples were collected from one replication only.

Root densities generally decreased with increasing depth, with the highest concentration of roots in the first 300 mm soil layer. Between 70 - 85% of the roots occurred in the upper 600 mm zone, independent of genotype and water treatment. Studies by Fulton (1970) showed similar results: late in the season 60% of the roots were located in the top 680 mm of soil. Although variation in the data is evident, it is clear that water stress (W3 and W5 treatments) did not substantially stimulate rooting depth in any genotype or planting. In some instances the root densities in the deeper soil layers were higher in the wet treatments than in the dry treatments for the same genotype. Comparing the W1 and W5 treatments, it appears that for most genotypes and plantings the root densities in the shallowest layer (0 - 300 mm) were lower for the W5 treatments (Figures 8.1 to 8.6), but the trend is not consistent. This might indicate that some roots died as a result of the dry conditions in that zone.

Late Harvest, the standard late genotype, in most instances had higher concentrations of roots in the deeper zones than the genotypes to which it was compared in the same trial (e.g. Figures 8.3 and 8.5). Clear differences in deep-root penetration were not obvious between Up-to-date, the medium standard, and Late Harvest (figures 8.1 and 8.2). Up-to-date has been shown to

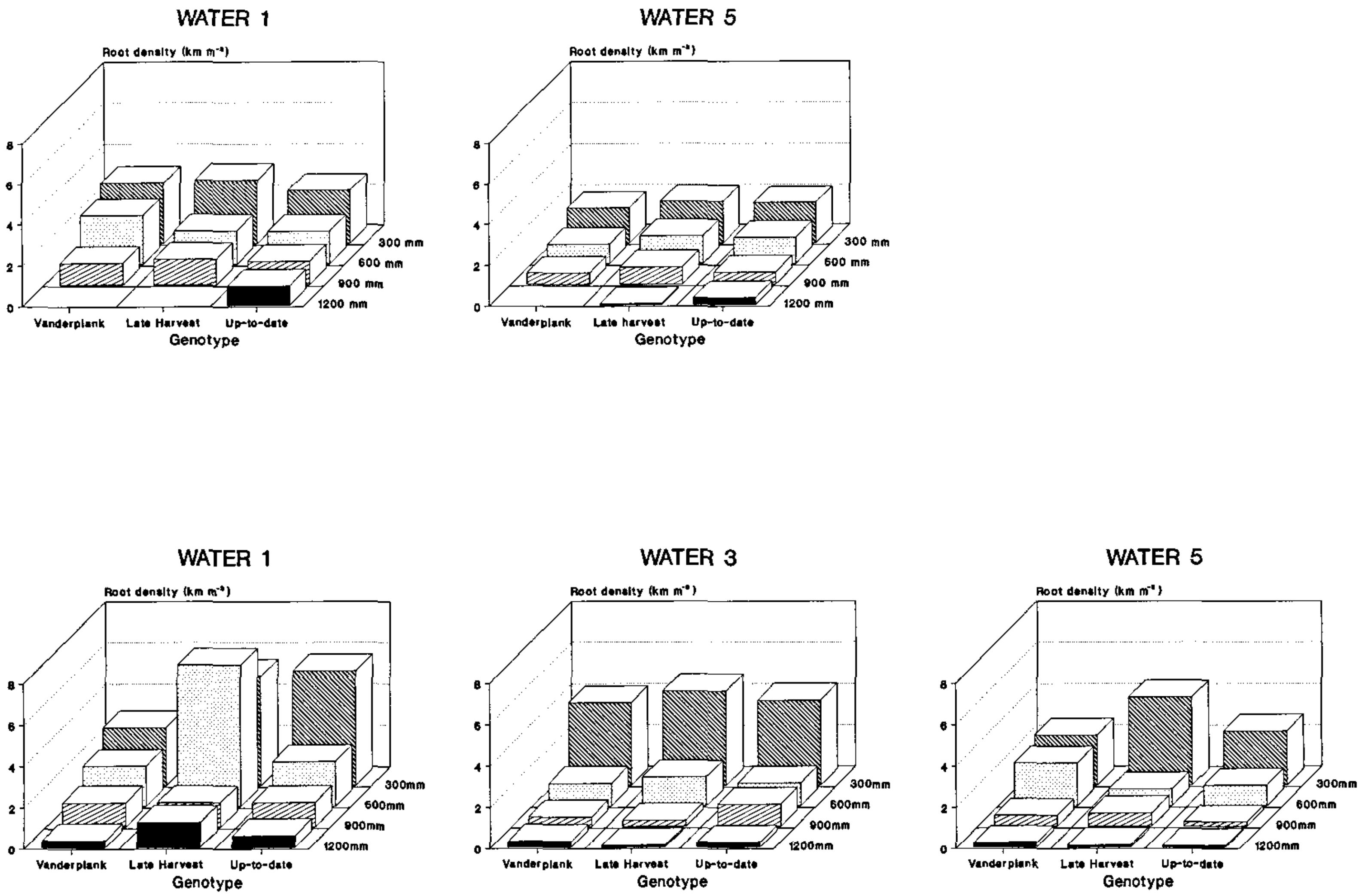


FIGURE 8.1 : Root densities of three potato genotypes during the 1992 spring (top) and 1993 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #1)

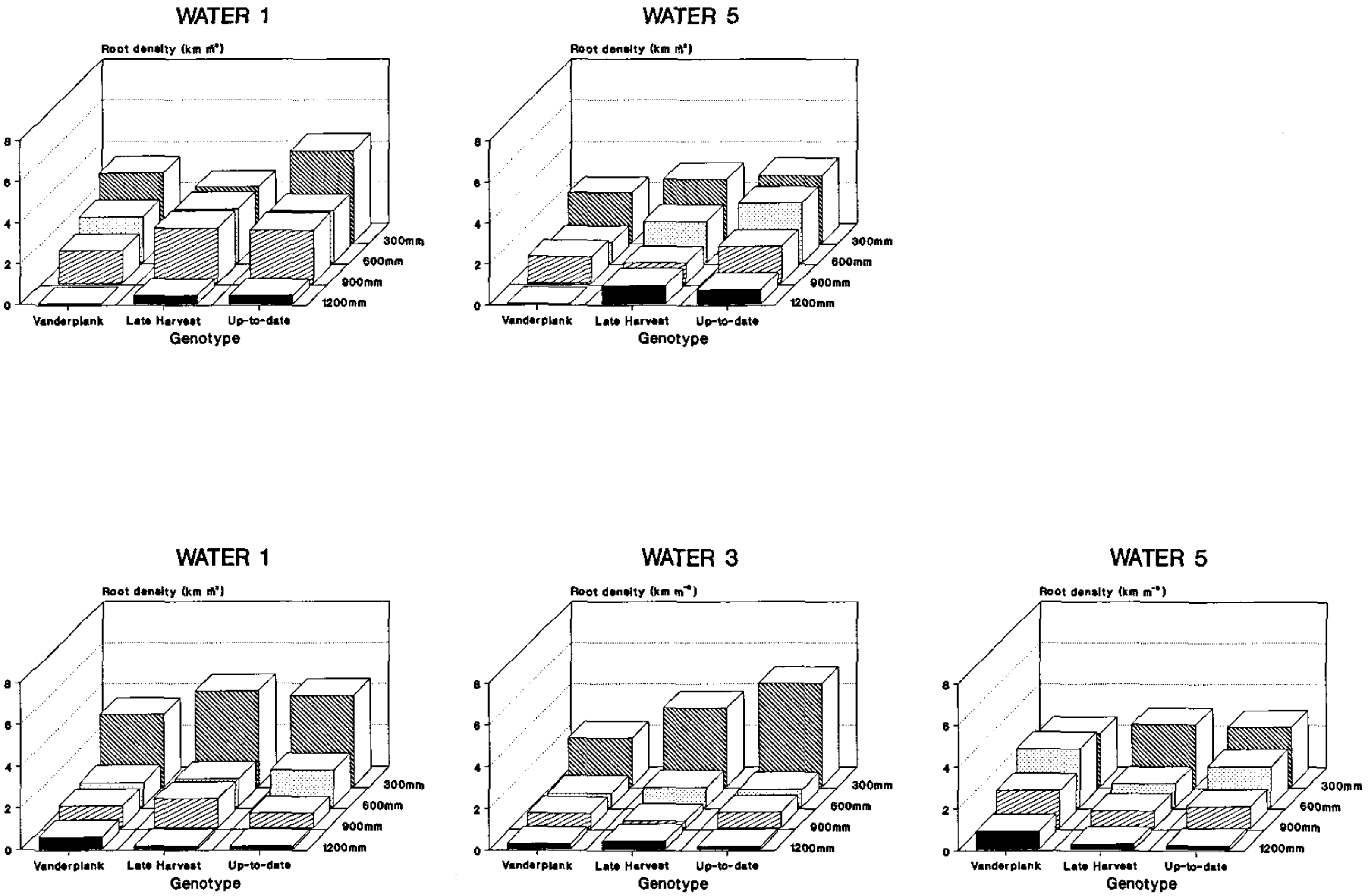


FIGURE 8.2 : **Root densities of three potato genotypes during the 1992 spring (top) and 1993 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #2)**

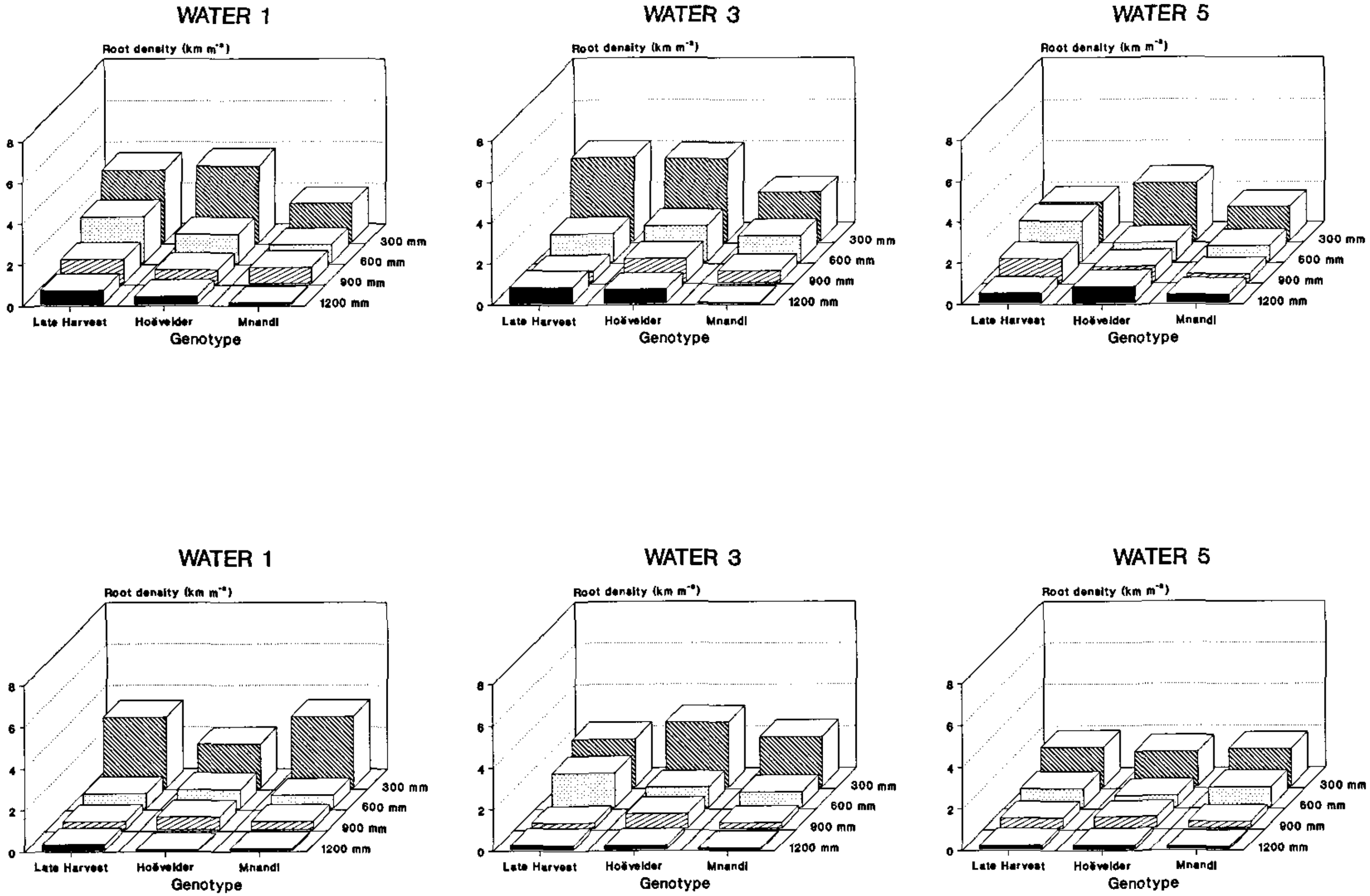


FIGURE 8.3 : Root densities of three late potato genotypes during the 1993 spring (top) and 1994 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #1)

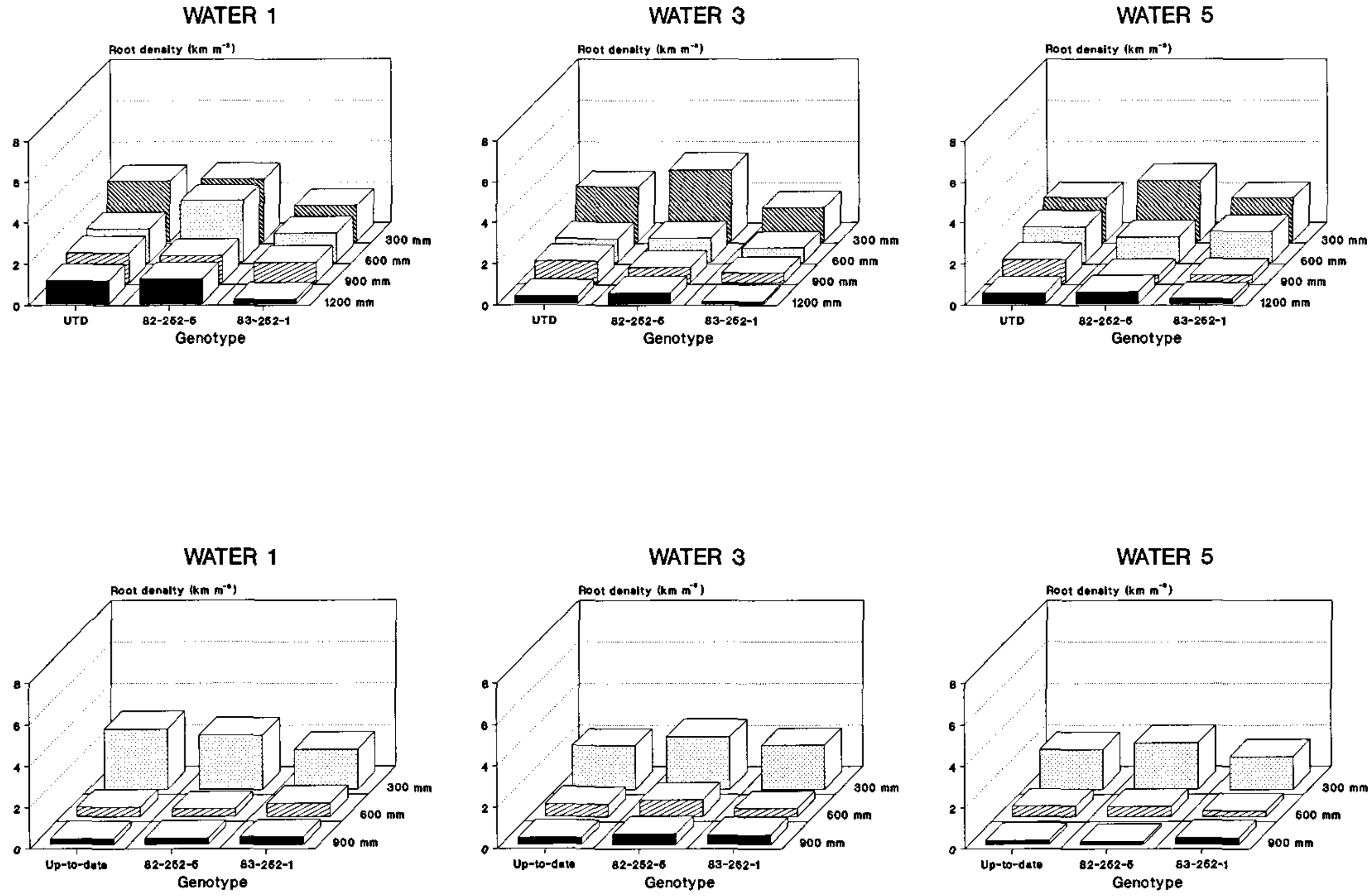


FIGURE 8.4 : **Root densities of three medium potato genotypes during the 1993 spring (top) and 1994 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #2)**

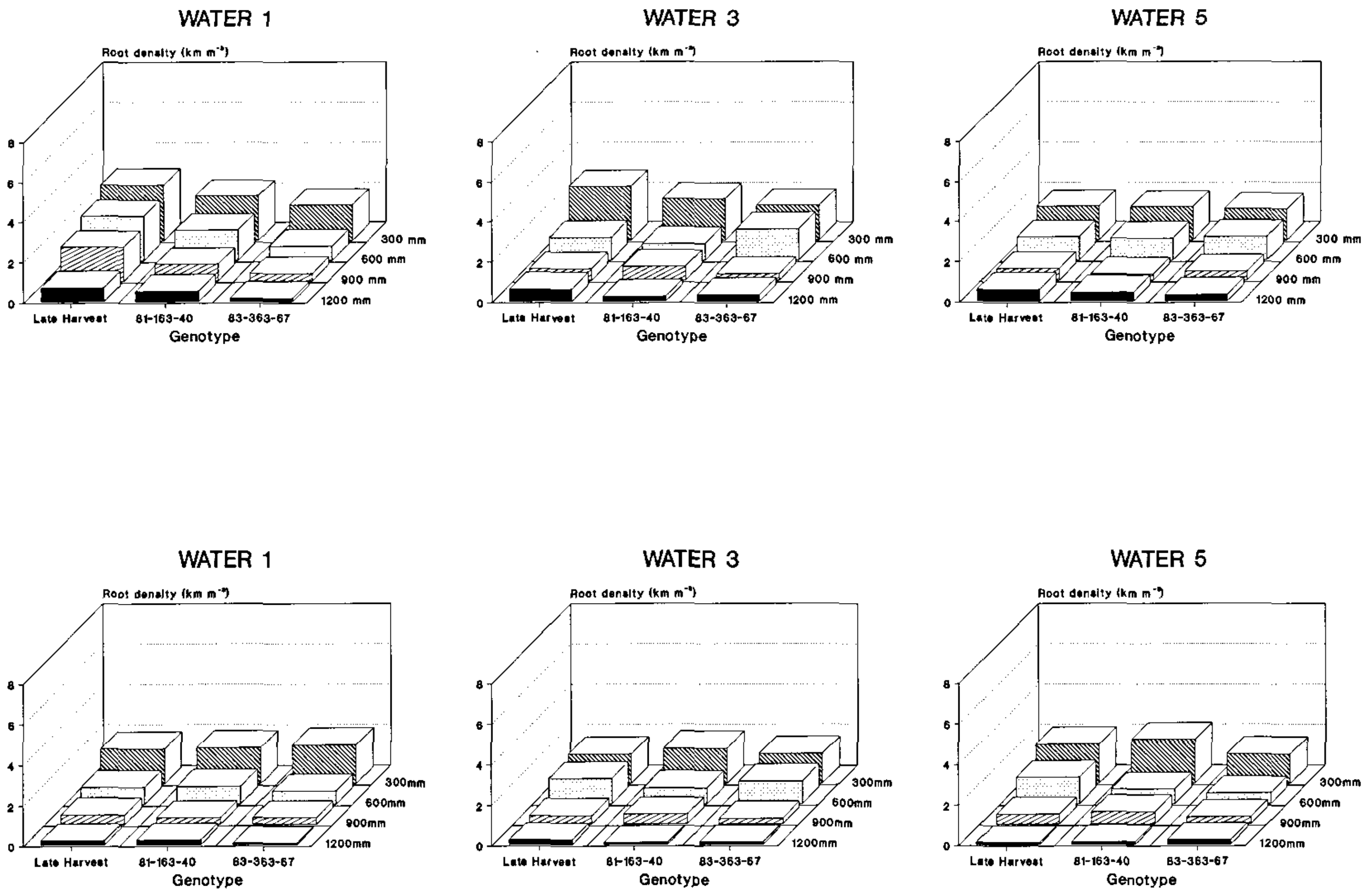


FIGURE 8.5 : Root length densities of three late potato genotypes during the 1994 spring (top) and 1995 autumn planting (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #1)

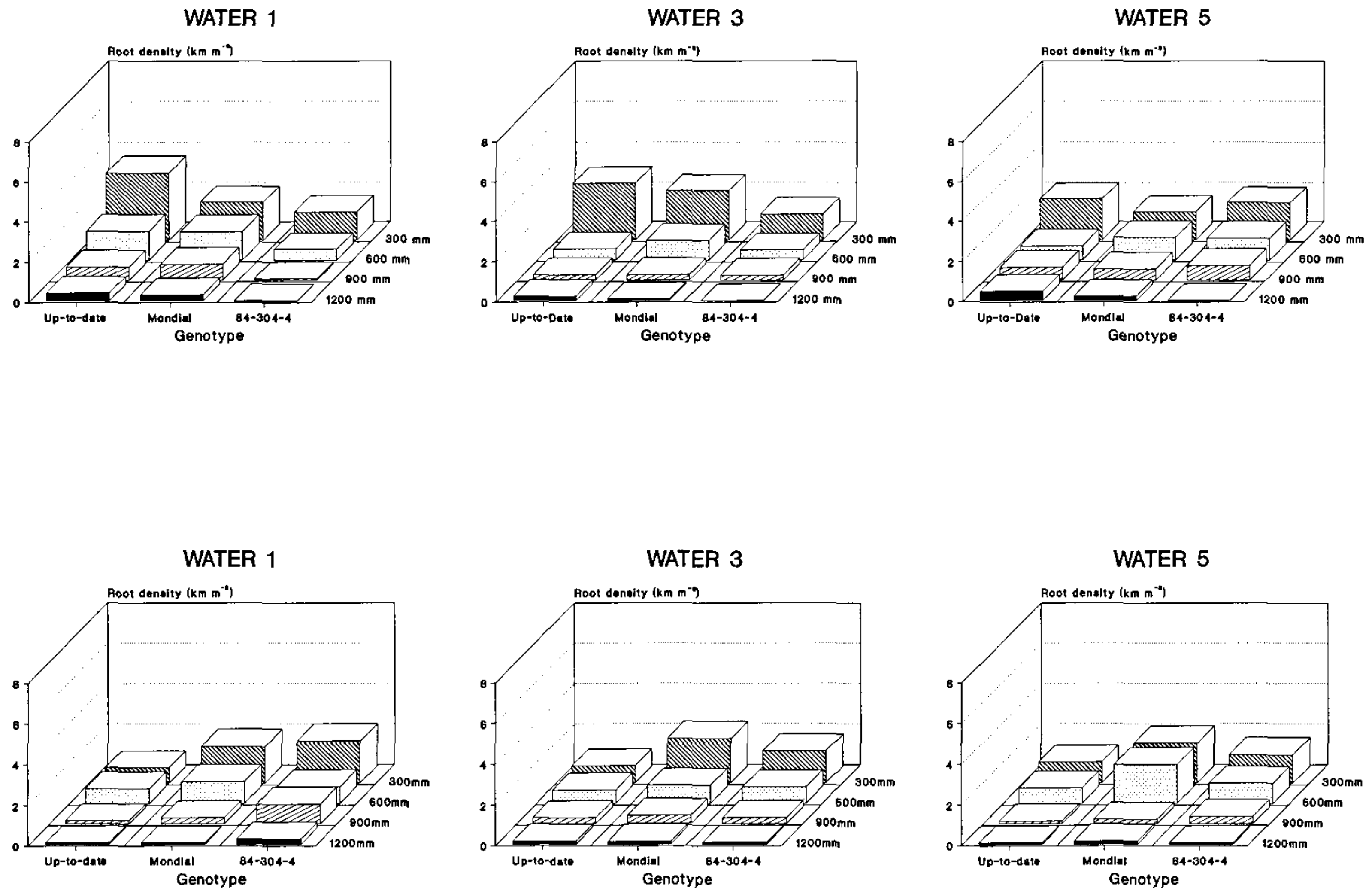


FIGURE 8.6 : Root length densities of three medium potato genotypes during the 1994 spring (top) and 1995 autumn planting (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #2)

be more drought susceptible than Late Harvest (Chapters 4 and 9), suggesting a poor relationship between drought tolerance and root distribution. Also Mnandi, a high-yielding genotype, even when water stressed, appears to have had fewer deep roots than both Late Harvest and Hoëvelder (Figure 8.3).

The genotype 83-252-1 appears to have had less roots in total, compared to 82-252-5 and Up-to-date, especially in spring plantings (Figure 8.4). However, indications that both 82-252-5 and 83-252-1 are more drought-tolerant than Up-to-date are presented in Chapter 9. In studies carried out by Levy (1983a) Up-to-date also had an extensive root system, but produced the lowest yield of all the genotypes as a result of water stress and high ambient temperatures.

It is clear that while seasonal differences were small, it appears from Figures 8.3 to 8.6 that slightly more roots were formed in spring than autumn plantings. This trend may be attributable to the shorter growing season in autumn, but the lower evaporative demand and lower water use in autumn might have contributed to the smaller root systems.

Depth of root penetration seems to be genetically defined, as almost the same number of roots were present in the 1200 mm soil layer, independent of the soil-water status. It must be borne in mind that all the treatments started off with wet profiles, which allowed the same degree of root development early in the season. Fulton (1970) concluded that differences in soil-water regime necessary for maximum yield of potatoes cannot be explained by the position of the major part of the root system. He found that potato yield was affected by a relatively small stress applied to only a portion of the total root system and suggests that potato roots may have a relatively low capacity for water absorption, and that most of the root system must have access to water at low tension in order to produce maximum yield. This was confirmed by the present study, as very little water seems to be depleted from the soil layers below 900 mm (Figure 7.4), although roots were present in that zone.

8.4 Conclusions

This study has shown that, although deeper root systems should have access to greater volumes of soil from which more water can be exploited, water stress did not stimulate deeper root systems in the genotypes studied. Between 70 - 85% of the total root system was located in the upper 600 mm of soil, independent of the genotype and water treatment applied. Variation in the data was inevitable, as only one replication per treatment was sampled, but clear differences in the extent of root systems for different genotypes were evident. The size of the root system did not appear to correspond with other drought tolerance characteristics in the genotypes evaluated in this study. Some of the genotypes, such as Mnandi and 83-252-1 for example, had smaller root systems, but were more drought-tolerant than many of the other genotypes.

If root systems do play a role in drought tolerance, the capacity of some genotypes to withstand drought is perhaps due to total root surface area differences (Tan & Fulton, 1985), which were not investigated in this study, as only the total lengths of the thicker roots (> 400 micron) were collected and measured.

A practical implication of these findings for irrigation scheduling is that the same rooting depth can be used in the calculation of plant-available water for all potato genotypes. Although some roots were present in the deeper soil layers, their contribution to water uptake was limited (Chapter 7). A maximum rooting depth of 600 mm is suggested for the calculation of plant-available water in irrigated potatoes.

CHAPTER 9

A QUANTIFICATION OF THE DROUGHT TOLERANCE OF POTATO GENOTYPES

9.1 Introduction

The sensitivity of potatoes to water stress is well documented (Doorenbos & Kassam, 1979; Van Loon, 1981; Coleman, 1986; Van Loon, 1986; Miller & Martin, 1990). Significant reductions in tuber yield and quality, for example, are almost certain consequences of drought stress (MacKerron & Jefferies, 1988; Jefferies & MacKerron, 1993; Adams & Stevenson, 1990; Haverkort *et al.*, 1990).

It is generally accepted that better yield and quality can be attained by the selection of cultivars that are better adapted to specific environments, such as drought and heat (Cother *et al.*, 1981). The development of drought-tolerant potato cultivars is one of the major objectives in hot tropical environments, where there is insufficient soil water during the growing season (Demagante, Harris & Van der Zaag, 1995). Various physiological parameters have been evaluated as indices for the screening of drought tolerance. These include changes in photosynthetic rate, stomatal resistance or conductance, leaf water potential and canopy temperature (Dwelle *et al.*, 1981; Wilcox & Ashley, 1982; Dwelle, 1985; Coleman, 1986; Vos & Groenwold, 1988; Schapendonk *et al.*, 1989; Sukumaran *et al.*, 1989; Vos & Groenwold, 1989; Spitters & Schapendonk, 1990; and Chapter 6 of this study). Selection for drought tolerance is usually difficult to achieve as drought tolerance cannot easily be related to one or more morphological or physiological aspects (Spitters & Schapendonk, 1990). Whether physiological screening methods are successful or not, it seems that field evaluations will always be necessary to verify the drought tolerance of genotypes.

Limited water is a major restriction to crop production in South Africa, as in many other semi-arid parts of the world. Therefore, the breeding of genotypes better adapted to drought is an important priority of the local potato breeding programme. This chapter deals with the evaluation for drought tolerance of potato cultivars and breeding lines used in the water-use trials discussed in Chapters 3 and 4.

9.2 Materials and methods

Classification of drought tolerance is usually based on relative tuber yield or yield reduction as a result of drought stress (Mahalakshmi *et al.*, 1990; Price, Jalaludden & Dilday, 1992; Jefferies & MacKerron, 1993; Demagante *et al.*, 1995). Tuber yield in water-limiting conditions is expressed as a percentage of yield produced with an abundant supply of water (Price *et al.*, 1992; Demagante *et al.*, 1995). Fischer & Mauer (1978) suggested a "drought-sensitivity index" to compare drought tolerance of genotypes. This index gives the reduction in yield of a specific genotype due to water stress relative to the average yield reduction observed for all the genotypes in that trial. The most drought tolerant genotype will therefore be the one with the lowest reduction in yield. The index is calculated with the following equation:

$$\mathbf{DSI = (1\text{-}Yd/Yw)/(1\text{-}\underline{Yd}/\underline{Yw})} \qquad \mathbf{(9.1)}$$

where

Yd = stressed yield of genotype
Yw = unstressed yield of genotype
$\underline{Yd}$ = mean stressed yield of all genotypes
$\underline{Yw}$ = mean unstressed yield of all genotypes

An index value greater than 1 indicates drought sensitivity relative to the mean, while a value less than 1 indicates drought tolerance. Since genotypes were compared over seasons (Chapter 4), it was decided to express the yield loss of genotypes relative to the yield loss recorded for the standard genotype in the same trial, rather than the mean. The mean of the combined yields for W1 and W2 were used to represent the unstressed yields, and the mean of the combined yields for W4 and W5 represented the stressed yields. Equation 9.1 was subsequently changed to the following:

$$\mathbf{DSI = (1\text{-}Yd/Yw)/(1\text{-}Yds/Yws)} \qquad \mathbf{(9.2)}$$

where

Yd = stressed yield of genotype, averaged for W4 and W5
Yw = unstressed yield of genotype, averaged for W1 and W2
Yds = mean stressed yield of standard genotype, averaged for W4 and W5
Yws = mean unstressed yield of standard genotype, averaged for W1 and W2

This method established a baseline for comparison, as the drought tolerance characteristics of the standard genotypes are known: Late Harvest, the late season standard, is a drought-tolerant local cultivar (Van der Mescht *et al.*, 1992; Rossouw & Waghmarae, 1995), while Up-to-date, the medium-season standard, is known to be fairly drought-sensitive, especially in hot climates (Levy, 1983a; Levy, 1983b; Jefferies & MacKerron, 1993). For the late-maturity class, index values =1 (the same as Late Harvest) or < 1 will indicate drought tolerance. Index values =1 for the medium-maturity class indicate drought-sensitivity similar to that of Up-to-date, while values <1 indicate better drought tolerance than Up-to-date.

9.3 Results and discussion

Drought-sensitivity indices (DSI) as well as percentage yield reduction for the medium- and late-maturity classes are presented in Tables 9.1 and 9.2, respectively. During the 1992 trials genotypes of both medium- and late-maturity classes were cultivated together under the same rain shelter. Since the 1993 spring planting genotypes were separated according to maturity class (see Chapter 3 for details). As the effect of drought on tuber yield was more severe in spring, the indices for spring and autumn plantings are presented separately in the tables.

TABLE 9.1 : **Drought sensitivity indexes (DSI) and percentage yield reduction recorded for different genotypes in the late maturity class during spring and autumn plantings**

Genotype	Planting	DSI*	% Yield** reduction	Planting	DSI	% Yield reduction
Late Harvest	Spring	1.000	59.7	Autumn	1.000	53.0
Up-to-date	1992	1.397	83.4	1993	1.034	54.8
Vanderplank		1.125	67.2		1.141	60.5
Late Harvest	Spring	1.000	62.9	Autumn	1.000	56.8
Hoëvelder	1993	1.120	70.5	1994	1.009	57.3
Mnandi		1.024	64.4		1.079	61.0
Late Harvest	Spring	1.000	53.1	Autumn	1.000	36.2
81-163-40	1994	1.277	67.9	1995	1.039	37.6
83-363-67		1.215	64.6		1.131	40.9
Average			66.0			50.9

* Drought sensitivity index, expressed relative to Late Harvest in the same trial

** % Yield reduction of each genotype, expressed relative to its own unstressed yield

TABLE 9.2 : **Drought sensitivity indexes (DSI) and percentage yield reduction recorded for different genotypes in the medium maturity class during spring and autumn plantings**

Genotype	Planting	DSI*	% Yield** reduction	Planting	DSI	% Yield reduction
Up-to-date	Spring	1.000	70.01	Autumn	1.000	38.5
Late Harvest	1992	0.853	59.8	1993	0.989	38.1
Vanderplank		0.737	51.7		0.811	31.2
Up-to-date	Spring	1.000	80.4	Autumn	1.000	30.2
82-252-5	1993	0.811	65.2	1994	0.964	29.2
83-252-1		0.850	68.3		0.879	26.6
Up-to-date	Spring	1.000	77.7	Autumn	1.000	34.2
Mondial	1994	1.004	78.0	1995	1.255	43.0
84-304-4		0.851	66.1		1.194	40.9
Average			68.6			34.7

* Drought sensitivity index, expressed relative to Up-to-date in the same trial

** % Yield reduction of each genotype, expressed relative to its own unstressed yield

From Tables 9.1 and 9.2 it is clear that the effect of drought was most severe in spring plantings, when the atmospheric evaporative demand was highest (Figure 3.1). For the late-maturity class, the genotypes Up-to-date, 81-163-40 and 83-363-67 were most drought-sensitive during spring plantings, while Vanderplank, Hoëvelder and Mnandi had DSI values only slightly greater than 1. In autumn plantings almost no genotypic differences in DSI values were evident, indicating that the direct effect of high temperatures or the combined effect of both high temperatures and high evaporative demand were mainly responsible for the differences. For the medium- maturity class all the genotypes were more drought-tolerant than the standard Up-to-date in both spring and autumn plantings, with the exception of Mondial (both plantings) and 84-304-4 (autumn). Since 84-304-4 did not experience normal growing conditions, as discussed earlier, no conclusions should be drawn from its performance in any trial. DSI values in autumn were closer to 1, indicating that the effect of stress was also less prominent than in spring plantings.

Late Harvest and Vanderplank, as well as the two breeding lines 82-252-5 and 83-252-1, had indices markedly less than 1 in spring plantings, indicating their better drought tolerance relative to Up-to-date. These results agree with the conclusions drawn in Chapter 4 regarding the ranking of genotypes according to their relative yields: in spring plantings, ranking according to relative yields depended on the water treatment, suggesting genotypic differences in their ability to cope at different levels of water stress, while in autumn the ranking did not change.

The very important difference between the meaning of the "relative tuber yields" (Chapter 4) and DSI's discussed in this chapter should be emphasized. The ranking of genotypes according to relative tuber yields deals with the physical yields obtained and does not take into account the reduction in yield due to water stress. Mnandi, for example, did not differ much from Late Harvest regarding its drought tolerance (DSI), but was constantly ranked higher than Late Harvest because of higher yields than Late Harvest recorded for all the water treatments. The ranking according to yield will therefore be the most useful criterion to producers selecting genotypes most suitable to their conditions, while the DSI will be of most value to plant breeders selecting for drought-tolerant parental material.

9.4 Conclusions

The effect of drought on tuber yield was most severe in spring plantings, when the atmospheric evaporative demand was highest. The late-maturity genotypes 81-163-40 and 83-363-67 were most drought-sensitive, while Hoëvelder and Mnandi compared favourably to Late Harvest, the drought tolerant standard. Vanderplank, 82-252-5 and 83-252-1 are the most drought tolerant and Up-to-date the most drought sensitive genotype in the medium-maturity class.

Genotypic differences in DSI-values were almost non-existent in autumn plantings, indicating that the effects of both high temperatures and high evaporative demand were mainly responsible for the differences in spring plantings.

The ranking of genotypes according to yield (Chapter 4) will be a useful criterion to producers selecting genotypes most suitable for their conditions, while the drought sensitivity indices (DSI) discussed in this Chapter will be of most value to plant breeders, who are selecting for drought-tolerant parental material.

CHAPTER 10

CALIBRATION AND EVALUATION OF THE SOIL WATER BALANCE (SWB) MODEL

10.1 Introduction

Limited water resources are a problem for most production sectors in South Africa. Irrigated agriculture is perceived to be the most inefficient of major water users. This is of major concern to farmers, including potato producers, who are dealing with a very drought-sensitive crop. Optimal use of irrigation water is only achieved by the application of effective irrigation scheduling. According to surveys carried out among potato producers, irrigation scheduling was consistently listed as an important yield-limiting factor (PPO, 1995). It is, however, also evident that most irrigators do not schedule irrigations (Annandale, *et al.*, 1996) and base their decision of when and how much to irrigate on experience only. There could be many reasons for this trend but Annandale *et al.* (1996) have concluded that the majority of farmers do not expect a net benefit from applying irrigation scheduling technology. A lack of simple, quick and reliable irrigation scheduling techniques seems to be another important reason why farmers do not schedule irrigations.

Direct measurement of soil-water content gives the best estimate of plant water use, but this method is usually time consuming, requires calculations and is often impractical on a large scale. Other methods, like A-pan evaporation in combination with crop factors and estimations from long-term evaporation (Green, 1985) are season-dependent and may not be reliable (Annandale & Stockle, 1994). The A-pan and crop factor-method assumes that crop development is dependent only on calendar time and that water use is determined only by atmospheric demand, which is certainly not the case (Campbell, 1977). Crop development is mainly dependent on thermal time but is also influenced by other factors such as water supply and evaporative demand. Water use is not only dependent on atmospheric demand, but also on the supply of water from the soil-root system (Annandale *et al.*, 1996).

User-friendly irrigation scheduling models may fulfill the need for irrigation management aids, as they mechanistically integrate our understanding of the soil-plant-atmosphere continuum. The many models available for soil-water budgeting differ greatly in their complexity, in the inputs needed and in their degree of accuracy (Kruse, Ells & McSay, 1990; Larsen *et al.*, 1984). In order to make accurate estimates of plant water use, the model should grow a realistic canopy and root system, split potential evaporation and transpiration and take the water supply from the soil-root system, as well as the demand from the canopy-atmosphere-system into account.

Penman-Monteith reference crop evaporation used in combination with a mechanistic crop growth model will provide a good estimate of the soil-water balance. Due to the specialist knowledge and inputs required to follow this approach, it has previously been out of reach of most irrigators on farm level. The ideal model would therefore require a simple interface for the user, while still using an accurate mechanistic approach which will ensure reliable simulations.

The aim of this chapter was to calibrate a generic crop irrigation scheduling model, the Soil Water Balance (SWB) model (Annandale *et al.*, 1996; Benade, Annandale & Van Zijl, 1996) for potato crops and to evaluate its performance on an independent data set.

10.2 Model description

The SWB model is based on an improved version of the model described by Campbell & Diaz (1988). The model is briefly discussed, with a more detailed description presented by Campbell & Stockle (1993).

The generic crop model is user-friendly and simple to operate, yet a mechanistic rather than empirical approach is followed in order to adhere to the accuracy required and to achieve a degree of transferability. Crop dry-matter production is calculated from the amount of transpiration, since yield is directly related to transpiration (corrected for vapour pressure deficit) in high-radiation climates (Tanner & Sinclair, 1983; Tan & Fulton, 1985):

$$\mathbf{Y = k\ T\ /\ VPD} \qquad \mathbf{(10.1)}$$

where Y is the dry matter produced (kg m^{-2}), k is a crop-specific constant (kPa) (the vapour pressure deficit corrected dry matter:water ratio), T is transpiration (kg m^{-2} or mm) and VPD the vapour pressure deficit of the atmosphere (kPa).

Dry matter production is also related to radiation intercepted by the foliage. The model calculates both the radiation- and water-limited growth on a daily time step and accepts the lesser of the two.

The dry matter produced is partitioned between roots, stems, leaves and harvestable yield. Preferential partitioning of assimilates to the different plant organs is dependent on phenological stage, which is calculated from thermal time and influenced by water stress. When the plants are exposed to water stress, assimilates are partitioned in favour of the roots, stimulating root growth at the cost of leaf expansion. Water stress conditions result therefore in smaller canopies and senescence is also enhanced.

A multi-layer soil component is used, which ensures a realistic simulation of the infiltration and crop water-uptake processes. A cascading soil water balance is used. When measurements of soil-water content or canopy fractional interception are made during the season, these can be entered into the model and the simulation will be corrected.

Potential evapotranspiration is divided into potential evaporation and potential transpiration by calculating radiant interception from the simulated leaf area. This represents the upper limits of evaporation and transpiration, which will only proceed at these rates if atmospheric demand is limiting. If actual transpiration, relative to potential transpiration, is less than the specified stress index, the crop is considered to be water stressed.

Transpiration rate depends on the atmospheric evaporative demand, soil-water potential and fractional interception of solar radiation by the crop canopy. Fractional interception (FI) is calculated from the leaf area index (LAI), using eq. 10.2:

$$\mathbf{FI = 1 - exp\ (-Kc\ LAI)} \qquad \mathbf{(10.2)}$$

where Kc represents the solar radiation extinction coefficient, a crop-specific constant. Leaf area index is calculated from the dry matter partitioned to the crop canopy (eq.10.3). Canopy dry matter (CDM) consists of the total mass (kg m^{-2}) of stems and leaves. The leaf-stem partitioning factor p (m^2 kg^{-1}) describes the ratio of dry matter partitioned between the leaves and stems.

$$\mathbf{LAI = SLA\ CDM\ /\ (1+p\ CDM\ )} \qquad \mathbf{(10.3)}$$

SLA represents the specific leaf area, or the leaf area per unit dry mass of the leaves (m^2 kg^{-1}).

10.3 Inputs required

As the model is fairly simple, the input data required are limited and usually easily obtainable (Annandale *et al.*, 1996). The following soil, crop and daily weather inputs are required:

1. ***Soil parameters*** needed for each soil layer:

    1.1 volumetric water content at field capacity
    1.2 volumetric water content at permanent wilting point
    1.3 initial water content

2. *Crop parameters:*

- 2.1 cardinal temperatures (base and optimum temperatures for development in °C)
- 2.2 thermal time requirements (in degree days) for
  - * emergence
  - * onset of the reproductive stage
  - * transition period
  - * leaf senescence
  - * crop maturity
- 2.3 VPD corrected dry matter:water ratio (kPa) (Tanner, 1981)
- 2.4 maximum rooting depth (m)
- 2.5 canopy solar radiation extinction coefficient (Kc)
- 2.6 radiation use efficiency (kg MJ^{-1})
- 2.7 assimilate partitioning parameters
- 2.8 maximum crop height (m)

3. ***Weather parameters***

- 3.1 maximum and minimum temperatures (°C)
- 3.2 precipitation (and irrigation) (mm)
- 3.3 solar radiation (MJ m^{-2} d^{-1})
- 3.4 vapour pressure (VP) *or* minimum and maximum humidity *or* wet and dry bulb temperatures
- 3.5 wind speed (m s^{-1}) and height of measurement (m)
- 3.6 latitude and altitude

The minimum weather data required are daily minimum and maximum temperatures. If not available, the other parameters are estimated according to the FAO recommended method (Smith, 1992) to enable the calculation of reference crop evapotranspiration (ETo).

10.4 Model calibration and evaluation

Calibration

Data sets containing complete growth analysis data which were collected from previous trials (1987 and 1990 autumn plantings) with the cultivar Up-to-date were used to obtain some of the crop parameters, as well as for model calibration. Thermal time requirements for the different phenological stages, radiation-use efficiency, specific leaf area and leaf-stem partitioning factors were calculated from these data. Parameters which could not be derived from the data sets were obtained from the literature or estimated. The crop parameters used in subsequent simulations are listed in Table 10.1.

Model outputs for the calibration data sets of root growth, LAI, total dry matter (TDM), harvestable dry matter (HDM) and simulated soil-water deficits are plotted along with observed values in Figures 10.1 and 10.2. Canopy size (LAI), dry matter production and soil-water deficits were simulated to an acceptable degree of accuracy for the well-watered treatment. For water-stressed conditions, however, tuber dry matter and total dry matter production are somewhat over estimated, although the LAI and soil-water deficit simulations were close to the observed values.

TABLE 10.1 : Crop parameters used for the cultivar Up-to-date as derived from data (autumn plantings) and the literature

Parameter	Value	Units	Method of estimation *
Canopy extinction coefficient (Kc)	0.55	-	Johnson *et al.* (1988)
Dry matter:water ratio (dwr)	6.80	Pa	Tanner (1981)
Radiation use efficiency (RUE)	0.00175	kg MJ^{-1}	Trebejo *et al.* (1990); Data
Base temperature (Tb)	2	°C	MacKerron & Waister (1985)
Light limited temperature	10	°C	-
Optimum temperature (Tm)	22	°C	Kooman (1995)
Thermal time : emergence	350	day degree	Data
Thermal time : reproductive phase	750	day degree	Data
Thermal time : maturity	2300	day degree	Data
Thermal time : transition	250	day degree	Data
Thermal time : leaf senescence	900	day degree	Data
Leaf water potential at maximum transpiration rate	-550	kPa	Data
Maximum transpiration rate	7	mm day^{-1}	Data
Specific leaf area	20.5	$m^2\ kg^{-1}$	Data
Leaf-stem partitioning factor	2.0	$m^2\ kg^{-1}$	Data
Total dry matter at emergence	0.005	kg m^{-2}	Data
Root fraction	0.10	-	-
Stem translocation	0.45	-	-
Root growth rate parameter	2.2	$m^2\ kg^{-0.5}$	-
Depletion allowed:			
Emergence	50	%	Data
Vegetative	50	%	Data
Reproductive	50	%	Data
Maximum rooting depth	0.6	m	Data
Maximum canopy height	1	m	Data

* *Model default values were used for parameters not obtained from literature or data.*

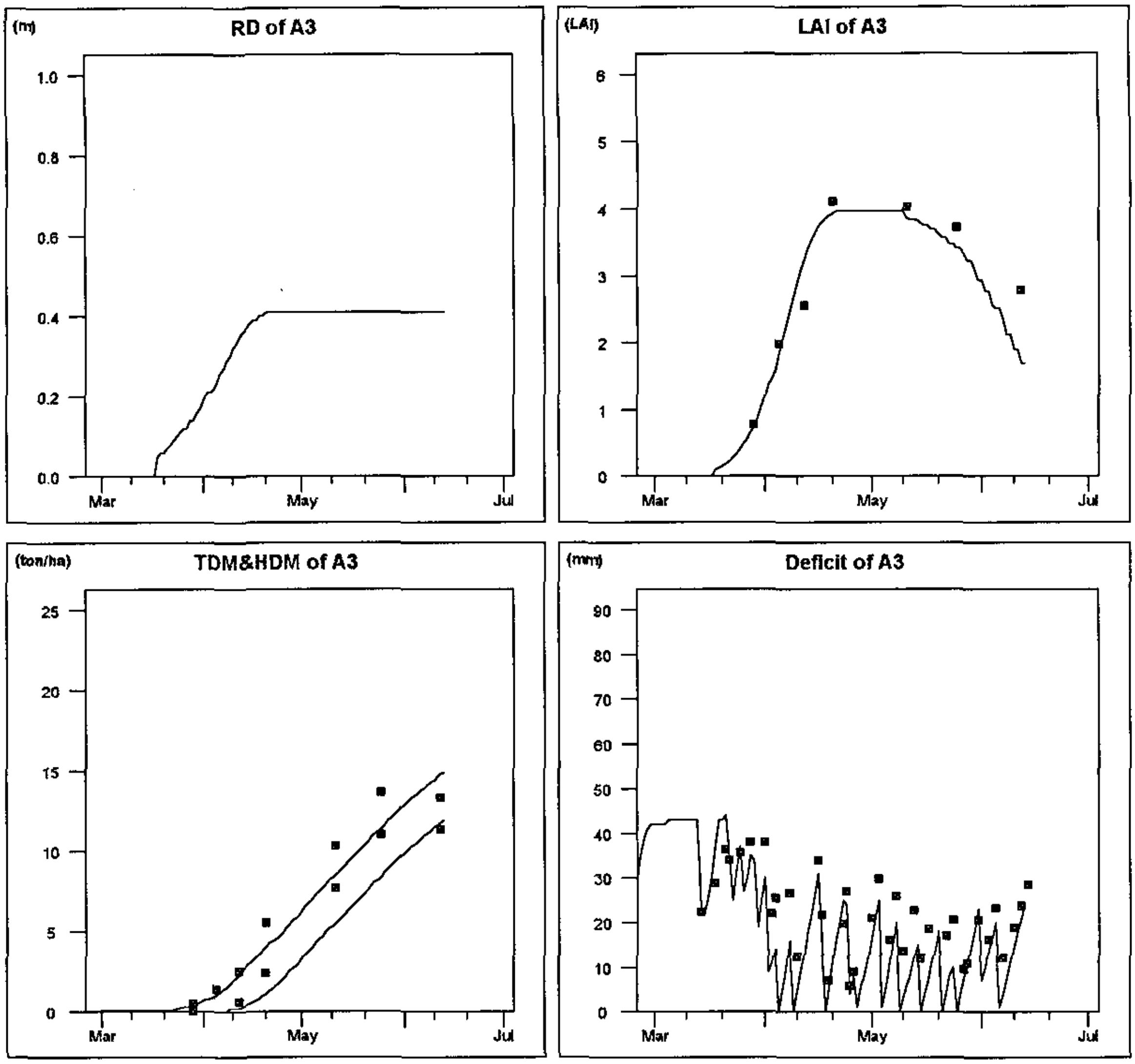


FIGURE 10.1 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for the calibration data set (autumn) of an unstressed potato crop

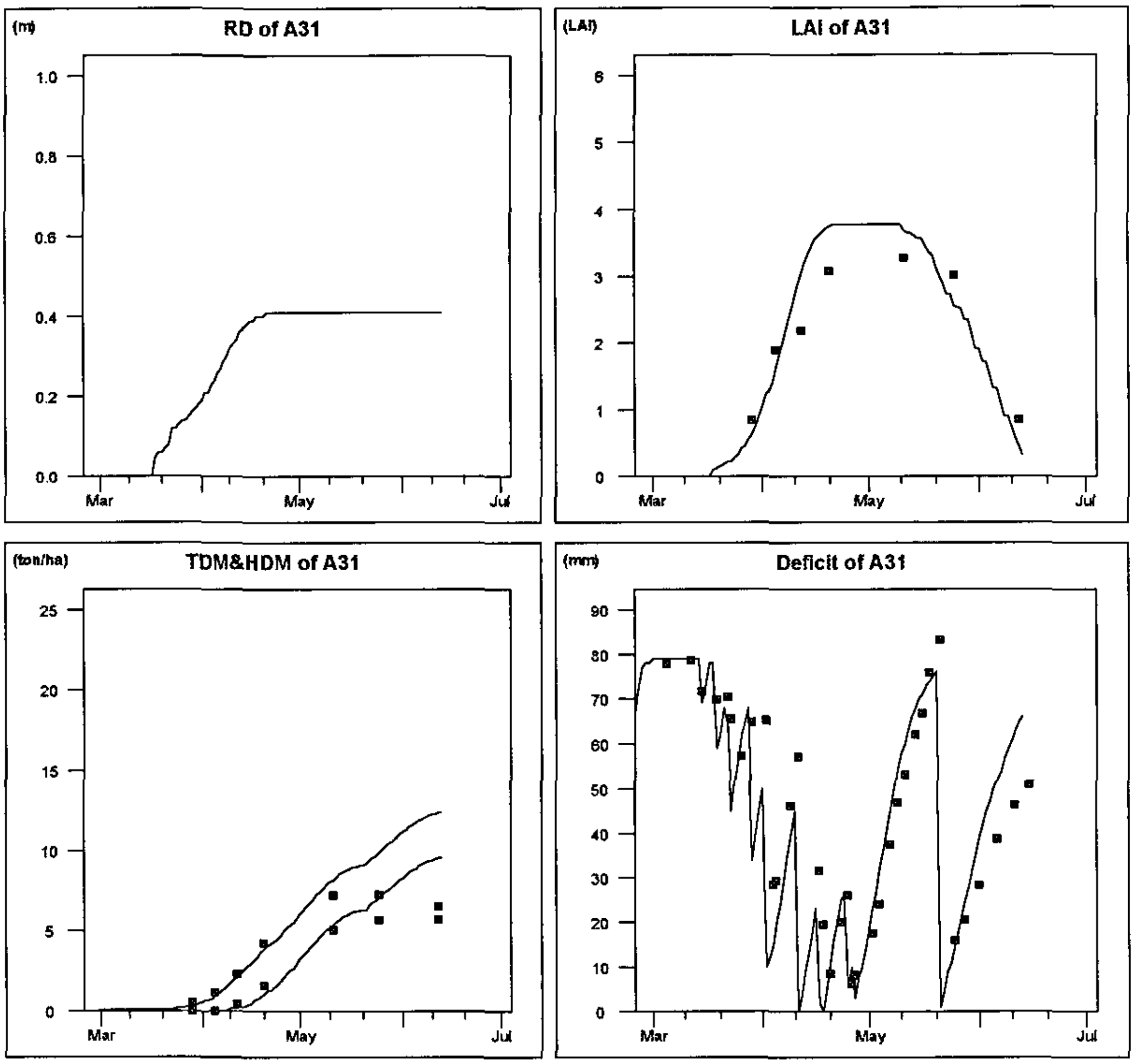


FIGURE 10.2 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for the calibration data set (autumn) of a water-stressed potato crop

Evaluation

Model evaluation was conducted on data sets for the Up-to-date cultivar, collected from the 1992 autumn and 1993 spring plantings of this project. Two irrigation treatments, a well-watered control (W1) and a water stressed treatment (W4 or W5) were used in the evaluation of the model.

Measurements were not made for some of the simulated parameters during this study. Dry matter accumulation of the different plant organs could, for example, not be determined as the number of replications was limited and plots were too small to conduct destructive growth analyses during the growing season. Total top dry matter and tuber dry matter were therefore determined only at the end of the growing season. Fractional solar radiation interception was measured three times during the 1993 spring planting only. For all the plantings soil-water content was recorded approximately three times per week.

Simulation outputs for both unstressed and water-stressed conditions, using the 1992 autumn data set, are presented in Figures 10.3 and 10.4. Only soil-water content and final tuber yield at harvest were recorded for this planting. Simulations pertaining to the accumulation of tuber dry matter and daily soil-water deficits were fairly accurate for both water treatments during this planting. This was also proved by the validation statistics carried out on the data (Table 10.2). It did, however, appear that the simulated LAI reduction at the end of the season was too rapid, as the simulated soil-water deficits for the last period were smaller than the measured values. As LAI was not measured, this could unfortunately not be confirmed.

The same crop parameters established from data collected during autumn plantings were used in the simulations for the 1993 spring planting. Maximum LAI, tuber dry matter and total dry matter production was under estimated and the simulated date of senescence was about one month earlier than the observed date (Figure 10.5). The smaller simulated canopy size also resulted in lower than measured values for water-use and soil-water deficits.

Growing conditions are known to be completely different during spring and autumn plantings:

in the spring crops are planted when temperatures are low and day lengths relatively short and the crop grows into hot, long day conditions towards senescence. The situation in autumn is completely the opposite to that for spring plantings: planting occurs in February, when temperatures are high and days are long, and the potato crop grows into cooler, short day conditions, until it is killed off by frost from middle May to early June (see Figure 3.1, Chapter 3 for long term climate of the trial site). The influence of photoperiod and temperature on potato development and the distribution of assimilates are known. Longer days postpone the onset of tuber initiation, enhance branching and extend the life cycle of potato plants, while short day conditions stimulate tuber initiation, reduce vegetative growth and lead to earlier senescence (Kooman & Haverkort, 1995). Temperatures also influence the partitioning of assimilates, especially in heat-sensitive genotypes, such as Up-to-date (Leskovar *et al.*, 1989; Wolf *et al.*, 1989). Under the high temperature conditions experienced during summer months (spring plantings) assimilates are partitioned in favour of haulm production at the expense of tuber growth, resulting in larger canopies and extended growth periods. Since SWB is a generic crop model, which does not take the effects of day length on crop growth and development into account, simulation errors in this regard should be expected.

Model performance could be enhanced by either adapting SWB to simulate these effects or, as a short term alternative, different sets of parameters could be developed for the two different plantings. After parameters such as the thermal time requirements for the different phenological stages were prolonged (reproductive phase 850 °Cd, maturity 2500 °Cd, transition 500 °Cd and leaf senescence 1300 °Cd) , simulations of tuber and total dry matter production, fractional interception of solar radiation (FI) and soil-water deficits improved considerably for unstressed conditions (Figure 10.6 and 10.8). For water-stress conditions, however, dry matter production and FI were under estimated (Figures 10.7 and 10.8).

Although leaf-area index was not measured, the simulated date of crop senescence was clearly far too early: the simulated leaf area index of the stressed treatment dropped to zero by late November, almost three weeks before the recorded date of haulm death. A proper calibration of the model for conditions in spring plantings could not be conducted, owing to the lack of complete data sets of crop development for such seasons.

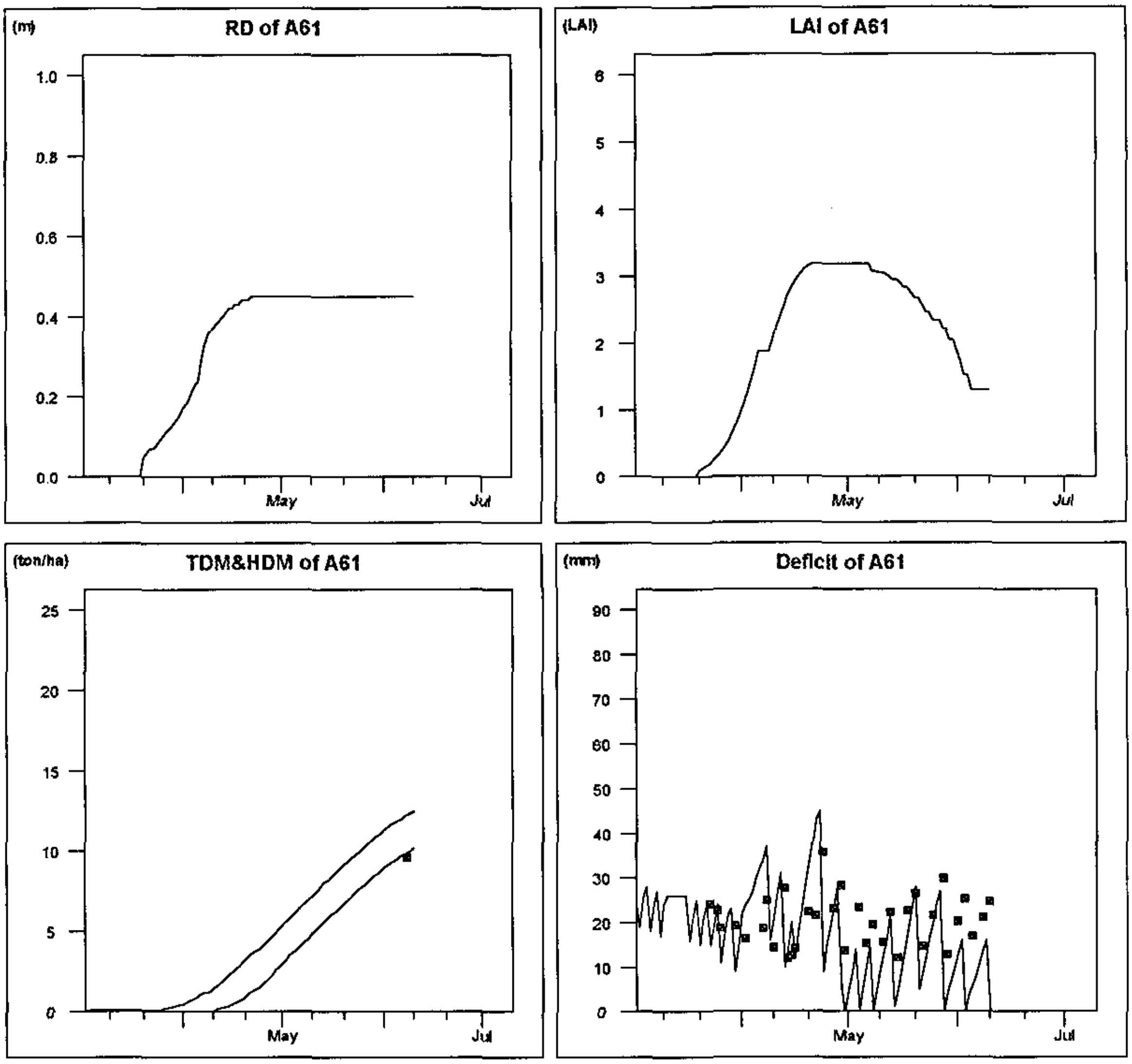


FIGURE 10.3 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for an independent data set (autumn) of an unstressed potato crop

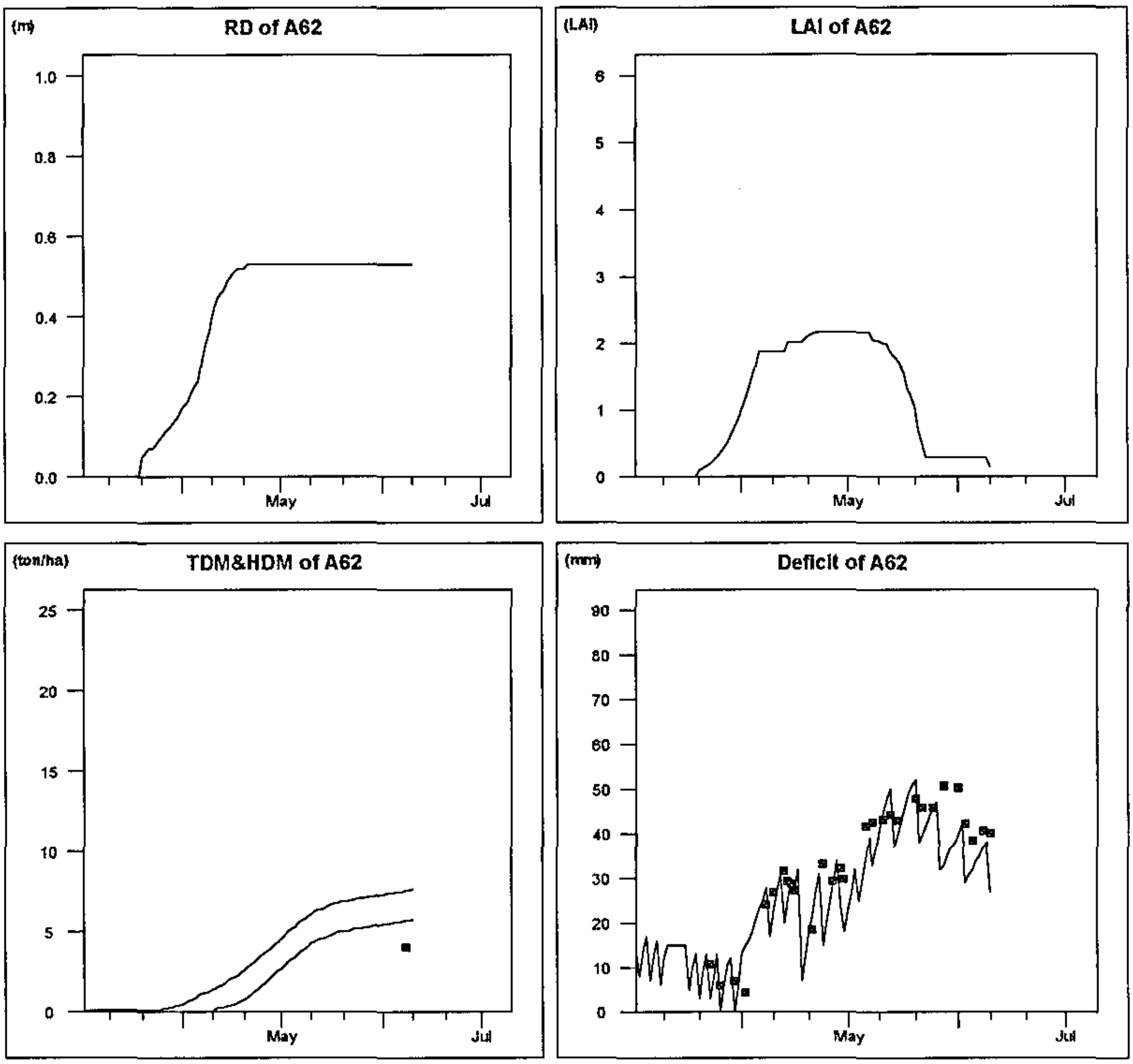


FIGURE 10.4 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for an independent data set (autumn) of a water-stressed potato crop

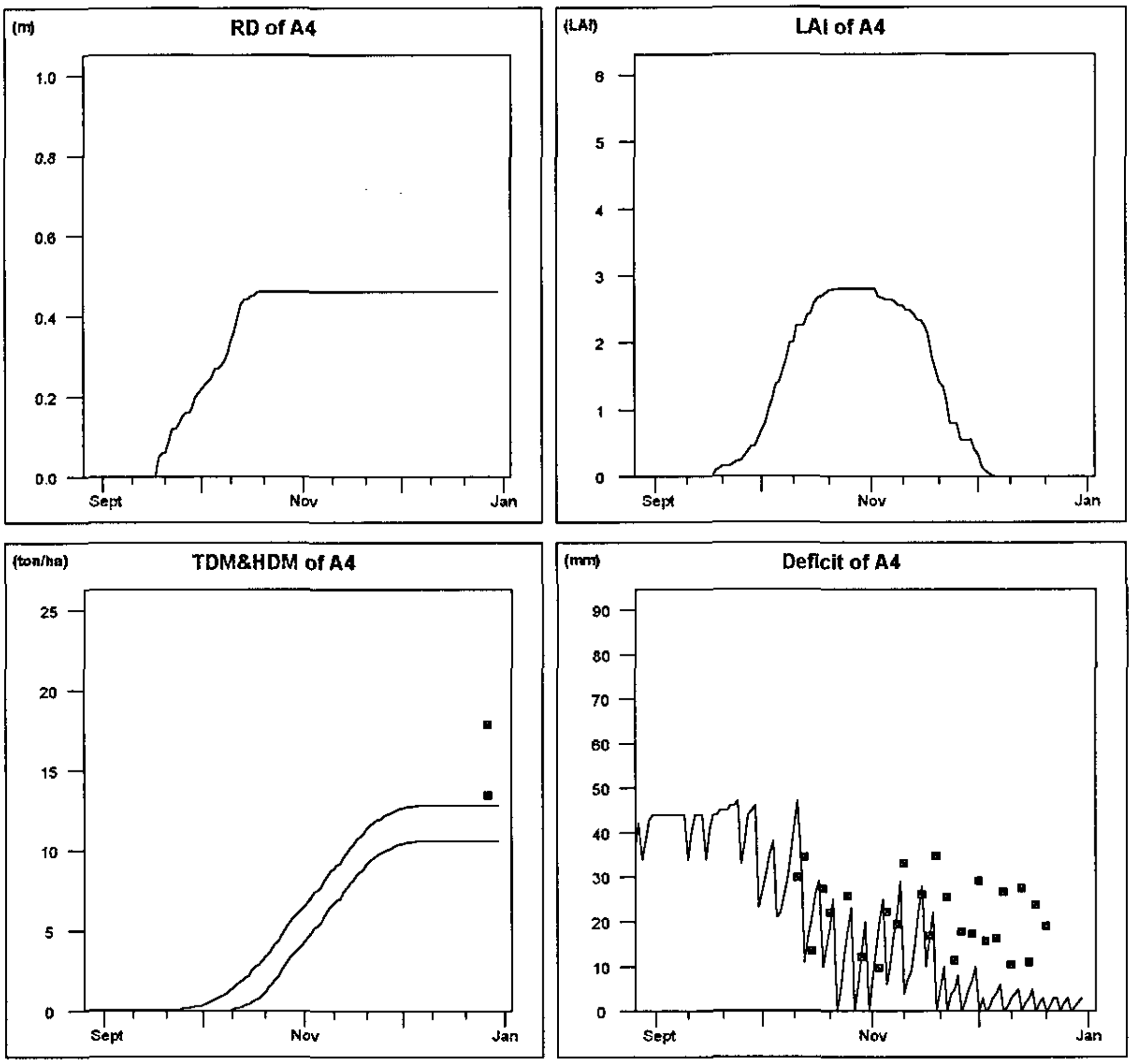


FIGURE 10.5 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm). Independent data set of an unstressed potato crop in the 1993 spring season with crop parameters for autumn

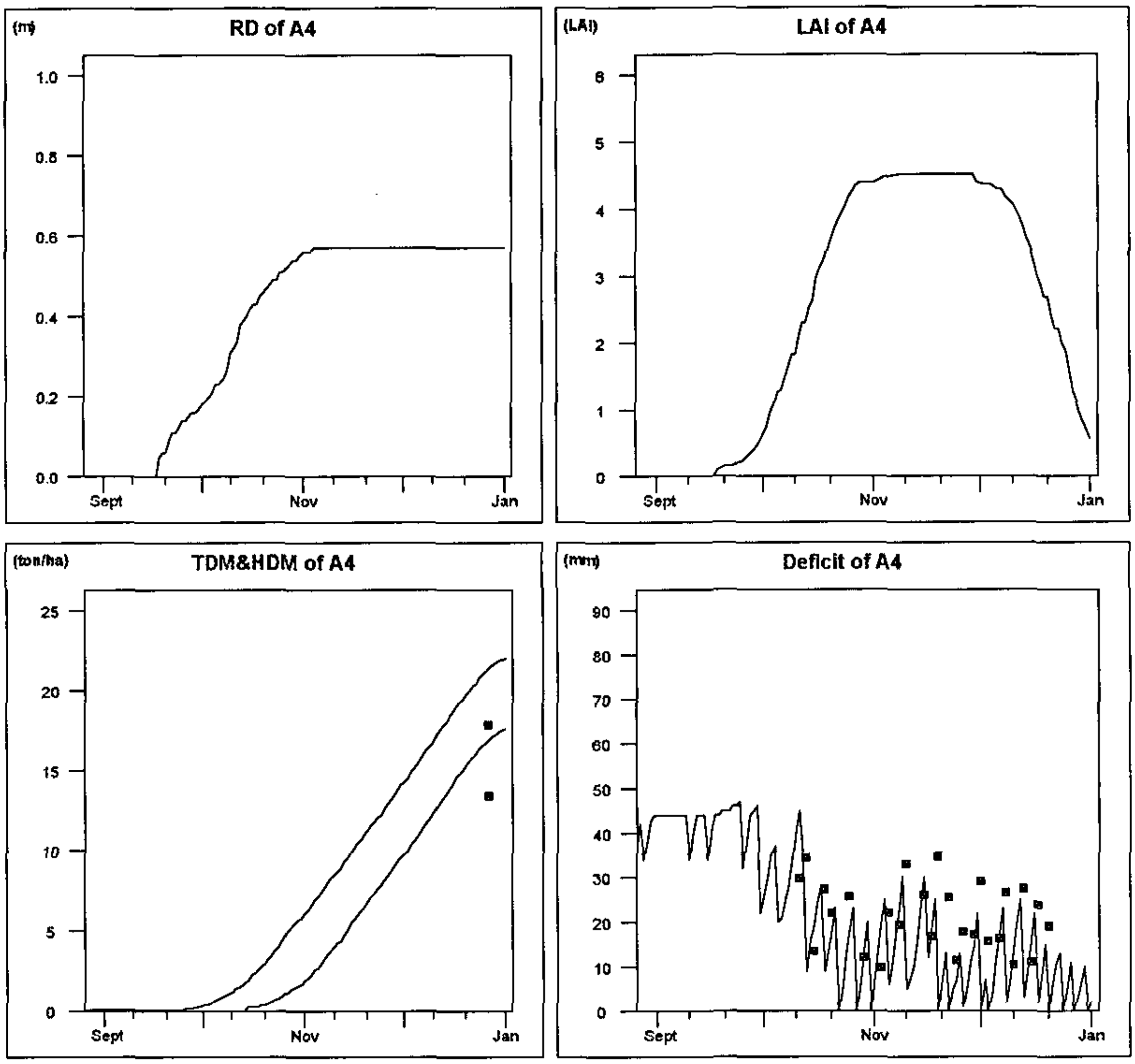


FIGURE 10.6 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm). Independent data set of an unstressed potato crop in the 1993 spring season after crop parameters were adapted

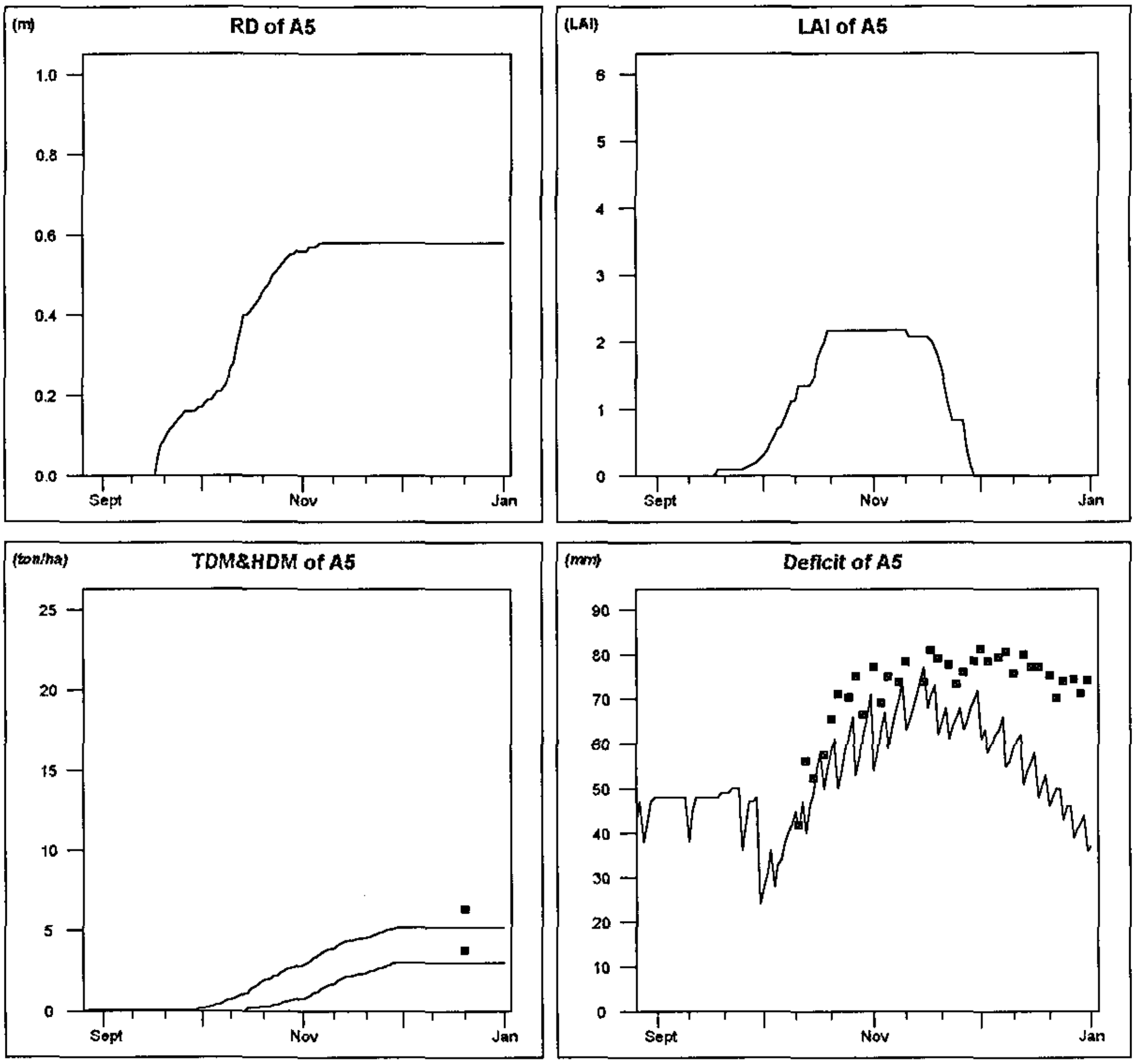
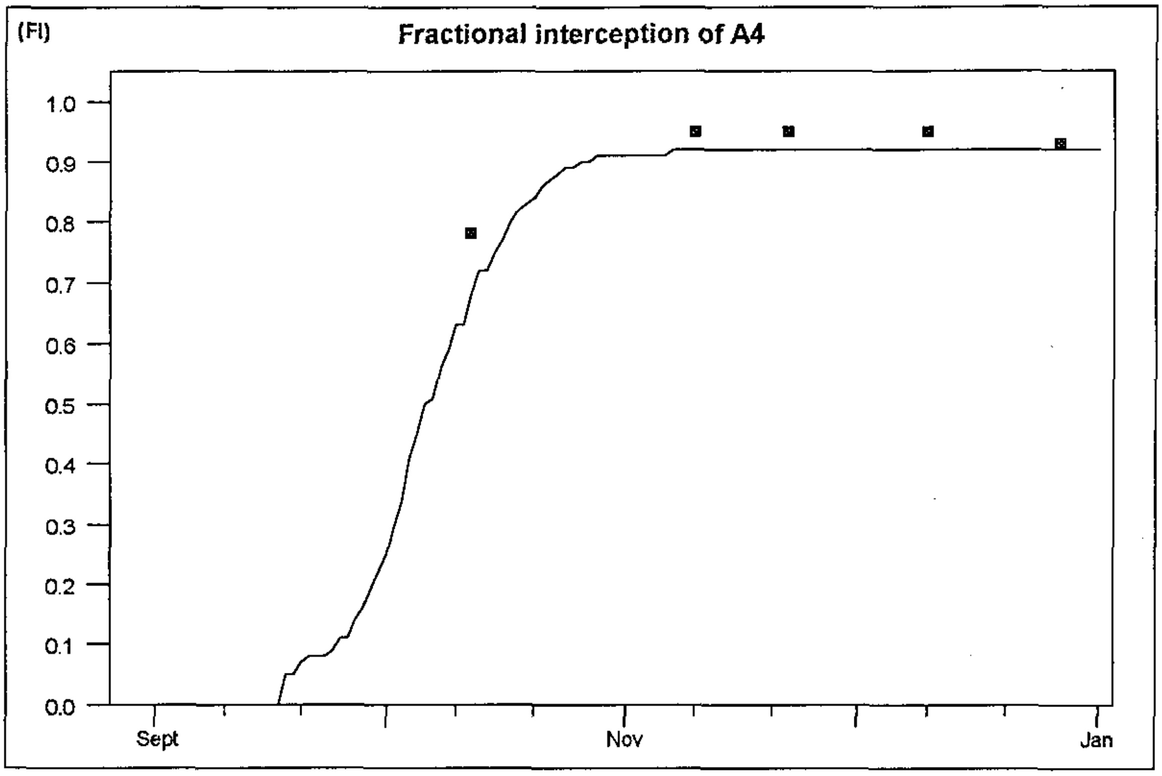


FIGURE 10.7 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm). Independent data set of a water-stressed potato crop in the 1993 spring season after crop parameters were adapted



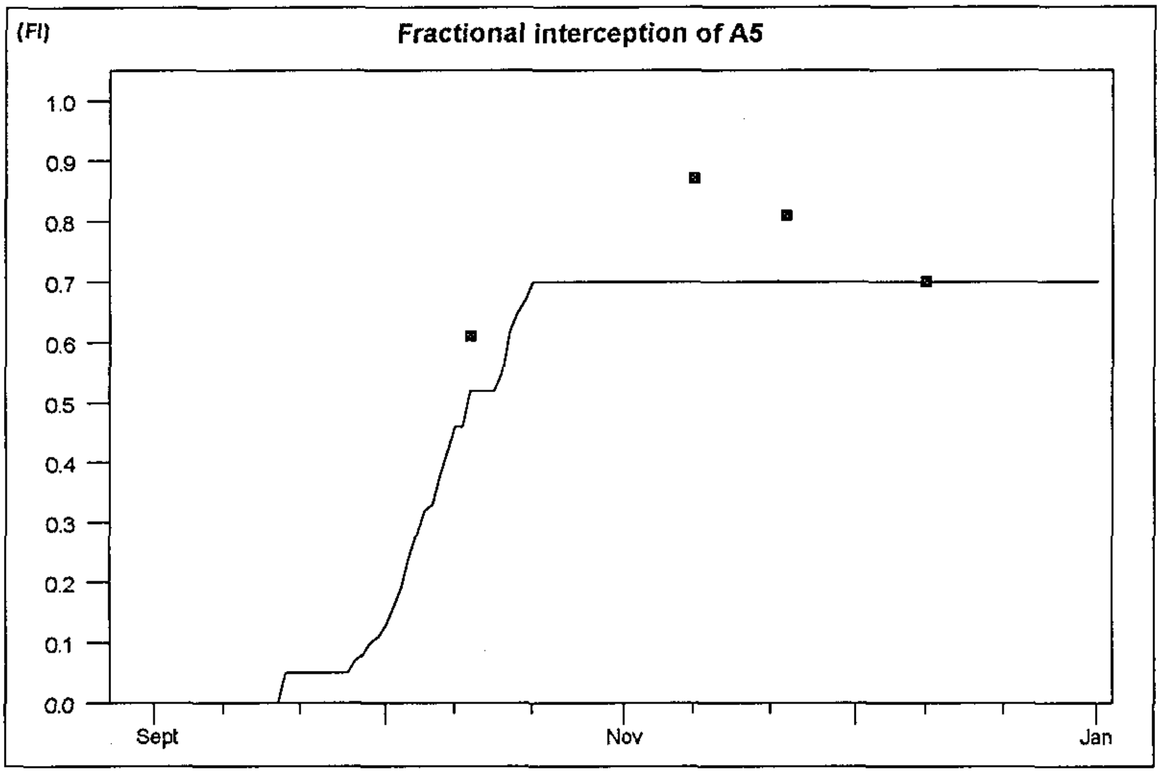


FIGURE 10.8 : Simulated (lines) and observed values (points) of fractional interception for independent data of an unstressed (top) and water-stressed (bottom) potato crop in the 1993 spring season after crop parameters were adapted

The five validation statistics proposed by De Jager (1994) were used to assess the accuracy of the SWB model when simulated soil-water deficits of the two water regimes were compared with measured values for the autumn 1992 planting. The statistical parameters compared include:

1. Slope through the origin (S)
2. Coefficient of determination (r^2)
3. Index of agreement of Willmot (1982) (D)
4. Root of the mean square error (RMSE)
5. Mean absolute error expressed as a percentage of the mean of the measured values (MAE)
6. The 80% accuracy frequency (D80)

Results of the model evaluations are given in Table 10.2. The last column lists the criteria set to be within an accuracy of 20%, a value recommended by Ritchie (1990) to be acceptable for simulation models. The accurate simulation of soil-water deficits for both water treatments was reflected by most of the parameters. This was also reflected by the plot of measured soil-water deficits against simulated values for both the unstressed and water-stressed conditions (Figure 10.9). For the water stressed treatment all the parameters were within the accuracy limits set in the last column of Table 10.2. The poor correlation between simulated and observed deficits during the last part of the growing season of the unstressed treatment, is reflected by the slope and 80% accuracy frequency values, which were slightly below the 20% reliability criterion.

The poor simulation of soil-water deficits late in the growing season of the unstressed crop should primarily be attributed to the incorrect simulation of canopy cover at that stage. Since the size of the canopy directly influences the rate of transpiration, water use will be simulated incorrectly when the canopy is senesced too early.

Table 10.2 : **Model evaluation of soil-water deficits simulated for potatoes subjected to two water treatments during the 1992 autumn planting. Statistical parameters used are the slope through the origin (S); coefficient of determination (r^2); index of agreement of Willmot (D); root of the mean square error (RMSE); mean absolute error expressed as a percentage of the mean of the measured values (MAE); the 80% accuracy frequency (D80) and the number of data points compared (n)**

Statistical parameter	Irrigation treatment		Reliability criteria
	Well-watered	Water stressed	
S	1.2	0.91	0.9 - 1.1
r^2	0.81	0.89	>0.8
D	0.91	0.97	>0.8
MAE (%)	15	9	<20
RMSE (mm)	4.33	4.49	-
D80 (%)	79	81	>80
n	28	27	

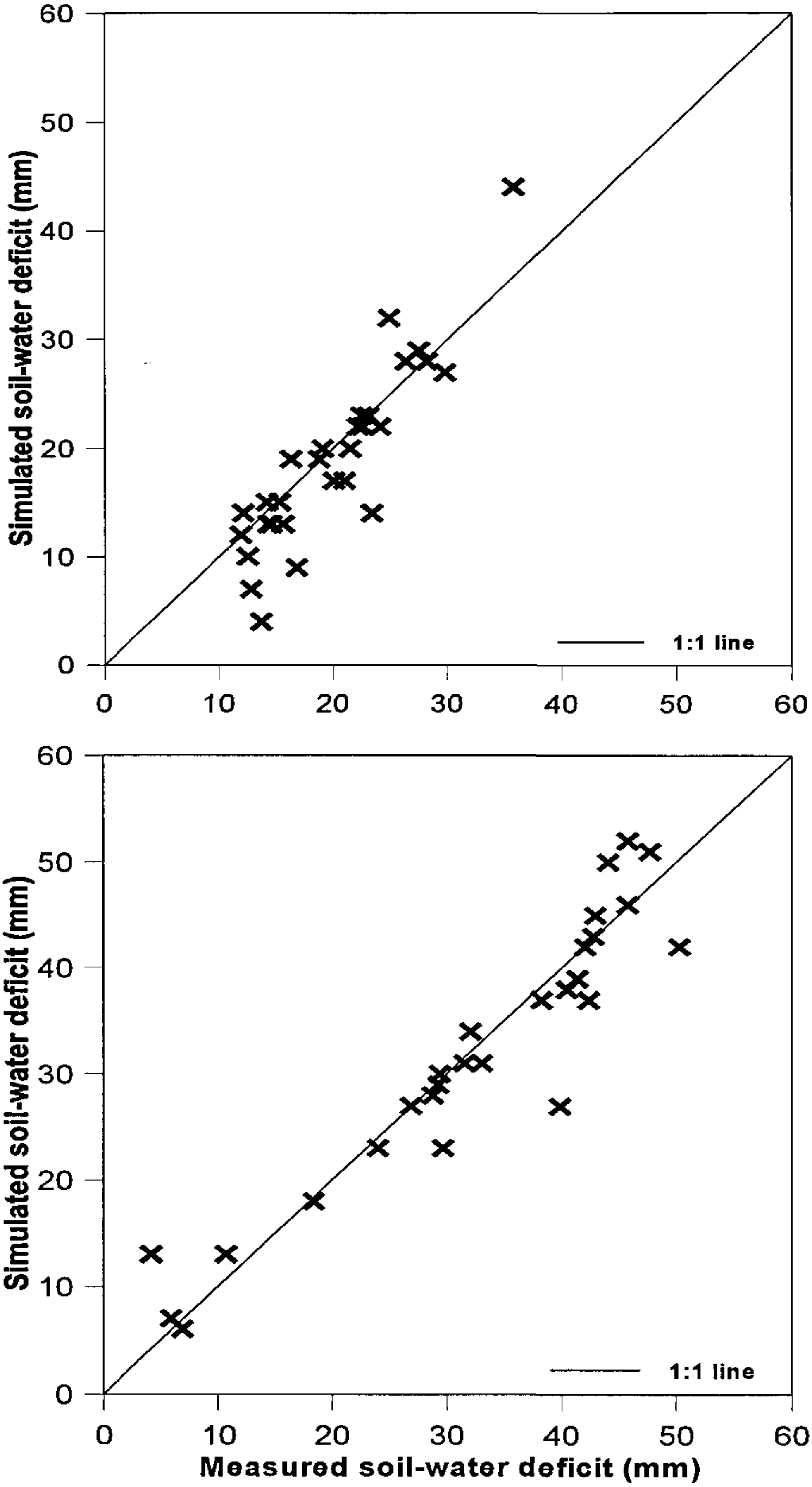


FIGURE 10.9: Simulated versus measured soil-water deficits recorded for potato crops under unstressed (top) and water-stressed (bottom) conditions for the 1992 autumn evaluation data set

10.5 Conclusions

The soil and atmospheric inputs required to run the Soil Water Balance (SWB) model are limited and easily obtainable, once the crop parameter file has been set up for the specific crop. Although the generic crop model is fairly simple, the soil-water balance was simulated to an acceptable level of accuracy for both well-watered and water-stressed autumn season potato crops. The date of crop senescence was, however, simulated too early and measured soil-water deficits at the end of the growing season were therefore generally higher than simulated values. Final tuber yield at harvest was also simulated reasonably well, but the level of accuracy obtainable with more mechanistic, crop-specific models should not be expected, as SWB is a generic crop model.

Simulations of crop growth and soil-water depletion were not accurate for spring plantings if the crop parameters determined for autumn plantings were used. Canopy size was underestimated and the estimated date of senescence was too early, resulting in incorrectly simulated soil-water deficits. This is probably because the generic crop model cannot simulate the effects of photoperiod and high temperatures on canopy development and assimilate distribution. After the thermal time requirements of different phenological stages were prolonged, simulations improved considerably, but for water-stressed conditions the canopy size, and therefore water use was underestimated.

The model should be a useful decision making tool for potato producers in helping them to decide when and how much to irrigate their crops on a daily basis. The latest Windows 95 version of the model also makes it extremely user friendly. Therefore, this tool will not only be accessible to extension personnel and advisors, but producers will be able to use it themselves.

Some aspects of the model that need to be addressed before final release include the following: (1) Determination of crop parameters for cultivars of different maturity classes. Since genotypes of the same maturity class showed only minor differences in water use within the same season (Chapter 7), there should be no necessity to determine parameters for each cultivar. (2) The inclusion of day length as a parameter to accommodate its effects on canopy development and date of maturity should improve the universal applicability of the model in different growing plantings (spring or autumn). As an alternative, separate crop parameters could be determined for spring or summer plantings.

CHAPTER 11

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The potato crop is well-known for its sensitivity to drought stress: yield and quality may be severely harmed by even mild water shortages at almost any growth stage of the crop. In South Africa, low annual rainfall and poor distribution of rain are major limiting factors for dry-land production of potatoes. Although about 73% of potato crops in this country are cultivated under intensive irrigation, plants are still often exposed to water- and heat stress due to the semi-arid climate.

The input costs of potato production are very high and producers are constantly seeking ways to reduce the risks in producing the crop. Regarding water use, two approaches could be followed to reduce the risks of yield and quality loss as a result of water stress: irrigation water could be used more efficiently and better adapted cultivars could be used.

As little is known about the water requirements of local potato genotypes, one objective of this study was to determine the amounts of water required by local potato genotypes for optimum production, as well as to determine the effects of water stress on tuber yield and quality.

Not all the genotypes could be included in the same trial because of limited space under the rain shelters where trials were conducted. Standard genotypes were therefore used in all the trials and the yields of genotypes were expressed relative the those of the standard genotypes. This method, although subject to some assumptions, enabled the comparison of genotypes over different years.

Genotypic yield differences in response to levels of water stress were mainly confined to the spring planting seasons, when temperatures and the atmospheric evaporative demand are higher than for autumn plantings. Some genotypes were clearly more adapted to water-stress conditions than others. Of the late genotypes Late Harvest and Mnandi performed best within the dry treatments, while Mnandi had the highest yields in the wetter treatments as well. Vanderplank, 82-252-5 and 83-252-1 had lower yields than most of the medium maturity class genotypes at the wet treatments, but had the highest yields when they were subjected to water stress. These findings challenge the suggestions of Jefferies & MacKerron (1993) that there is limited capacity for improved drought tolerance through breeding, other than improving potential yield: Late Harvest, Vanderplank, 82-252-1 and 83-252-1 had lower yield potentials than most of the genotypes they were compared with under favourable conditions, but had higher yields when they were stressed.

The ranking of genotypes according to yields attained at different water treatments is an important contribution to the current state of knowledge and will be valuable to producers in assisting them to select genotypes most suitable to their specific growing conditions. The ranking order of genotypes as a result of water treatments only changed for spring plantings, indicating that in autumn genotypes can be selected purely according to yield potential or specific needs of the end user. Another important implication of these findings is that, if producers have a choice between spring (or summer) and autumn (or winter) planting seasons, then there will be a larger range of high-yielding genotypes to select from for the cooler season. As yield differences between spring and autumn plantings were in most instances relatively small, high yields can usually be expected from autumn plantings, while the saving on irrigation water will be substantial.

In this study local potato genotypes were for the first time characterised according to drought tolerance and this objective was therefore fully met. Drought-tolerant genotypes were regarded as those that showed the lowest relative reduction in tuber yield when exposed to water stress. Mnandi, Late Harvest, Vanderplank, 82-252-5 and 83-252-1 were the most drought tolerant of the genotypes evaluated. Genotypic differences in drought tolerance were less pronounced in autumn, because temperatures and atmospheric evaporative demand were lower.

The drought-sensitivity index should be a valuable tool to plant breeders for the selection of drought-tolerant parental material in breeding programmes, but may be of less value to potato producers. A specific genotype, which is not classified as drought-tolerant, may because of a high yield potential, be ranked higher (according to yield) than a drought tolerant genotype, even in water-stress conditions. A typical example is Hoëvelder: this genotype is more drought- sensitive than Late Harvest as it shows greater yield reduction when exposed to water stress, but because of its high yield potential Hoëvelder will produce higher yields than Late Harvest under most conditions. A potato producer interested in a high yield will most probably select Hoëvelder, while a plant breeder will be more interested in Late Harvest as parental material in breeding programmes for drought tolerance.

The negative effect of water stress on tuber size was most severe in spring plantings, when temperatures and the atmospheric evaporative demand were higher. The yield of medium and especially large tubers were damaged by water stress, but genotypes did not respond differently to water stress within the same trial.

Water regimes apparently had less effect than temperature on tuber internal quality in spring plantings. Different water regimes had no effect on either tuber relative density or chip colour, presumably because of the negative effects of high temperatures on dry-matter and reducing-sugar content of the tubers. It appears that the application of more water to the wetter treatments did not cool the soil down sufficiently to compensate for the high ambient temperatures. According to Kincaid *et al.* (1993), the frequency of irrigation seems to be more important than the amount of irrigation in cooling the soil surface down. In the present study the frequency of irrigation was the same for all water treatments, because of the method of irrigation.

Chip colour was not affected negatively by water stress during autumn, as is often stated in the literature (Owings *et al.*, 1978; Kincaid *et al.,*1993; Shock *et al.*, 1993): chip colour generally improved with increase in stress levels for the genotypes studied. Low-temperature sweetening is suspected of being responsible for darker colours in the wet treatments: at the end of the tuber bulking phase minimum temperatures were usually lower than 10 °C, the temperature below which reducing sugars are reported to accumulate in tubers. Although not recorded, it can be assumed that soil temperatures were lowest for the wet treatments, as the soil surface was more completely covered by the larger crop canopies. Secondly, because wet soils have greater specific heat capacities they will heat up slower than dry soils, leading to lower temperatures (Trebejo & Midmore, 1990).

The objective to determine the effect of water regimes on tuber internal quality was only partly reached as, contrary to most reports in literature, water stress had no effect on tuber relative density and chip colour in spring plantings, while chip colour improved as a result of water stress in autumn. Firstly, the contradictory results are possibly attributable to the dominating effects of temperature on tuber quality. Secondly, the irrigation boom used does not resemble field conditions, due to the regular application of small amounts of water to dry treatments.

Although field screening methods, such as the technique used in this study, are preferred for the selection of drought-tolerant crops, the method is expensive, tedious, and the number of entries that can be included simultaneously is limited. From a breeder's point of view quick and reliable screening techniques that can be used on larger populations of early generation breeding material can be very useful. In this study photosynthetic rate (Pn) and stomatal resistance (Rs) were investigated as indicators of drought tolerance. Tuber yields correlated well ($r=0.87$ to $r=0.99$) with seasonal mean values of both these parameters for all the genotypes, but the regression functions that describe these relationships changed for plantings and genotypes. These variations are to be expected, as tuber yield is dependent on a number of physiological processes and Pn or Rs can at best only partly explain the final yields at harvest. The magnitude of decline in Pn or Rs in response to drought was, however, related to the magnitude of decline in tuber yield. These findings may be a significant contribution to early selection techniques for drought tolerance in crops.

The objective of finding suitable physiological parameters as early screening methods for drought tolerance in potatoes was reached, since the regression functions obtained from this study can in future be used to estimate the expected yield reduction of a specific genotype, once the reduction in Pn or increase in Rs for that genotype is established. Care should, however, be taken in the case of heat-sensitive genotypes such as Up-to-date, as the observed reduction in yield may be higher than the value estimated using the derived regression model.

Although these physiological measurements seem promising as methods for early screening of drought-tolerant material, they should be evaluated on independent data and on a wider range of more diverse material to prove their usefulness.

The vast differences in total water use between seasons and years were mainly as a result of differences in atmospheric evaporative demand. Normalising the water-use data for seasonal vapour pressure deficits narrowed the gap between years, but differences between spring and autumn plantings were still evident for the same genotypes. The reason for the remaining differences should probably be attributed to the fact that evapotranspiration and not transpiration data was used for comparisons.

The small differences observed between genotypes in water use can perhaps be explained by the way water use was calculated and by the method of irrigation used. Water use was mainly a function of water applied, as genotypes within the same maturity class received the same amount of water. Some of the genotypes might have been over- or under-irrigated in the process, and genotypic differences could only originate from differences in initial soil-water content or differences in soil-water depletion at the end of the growing season. Since genotypic differences in water use could not be determined with the irrigation technique used, this objective of the study was not reached. The irrigation boom is therefore not ideal for water use studies, although it is a valuable technique in screening for drought tolerance.

Water-use efficiencies were the highest for autumn plantings, because less water was lost through evaporation without contributing to the production of dry matter. The highest water-use efficiencies were generally recorded in the intermediate treatments (W2 and W3) for both plantings. The high-potential cultivars Up-to-date, BP1, Mnandi, 81-163-40 and Mondial had the highest efficiencies in autumn, independent of the water treatment applied, but in spring plantings the water-use efficiencies of genotypes were influenced by water treatments. Generally, Up-to-date, and 83-363-67 had the highest efficiencies in the wet to intermediate treatments, while the more drought-tolerant genotypes Vanderplank, Late Harvest and Mnandi had high efficiencies in all the water treatments in spring plantings. The medium-maturity genotypes 82-252-5 and 83-252-1 had the highest efficiencies in the driest treatments.

Rooting density in deep soil layers was not related to drought tolerance for the genotypes studied: both Mnandi and 83-252-1, two drought tolerant genotypes, had the lowest root densities throughout the entire soil profile, while Up-to-date, a drought-sensitive genotype had an abundance of roots, even at a soil depth of 1200 mm. These findings implicate that, although root distribution was slightly changed by water regime, root development is not a suitable indicator of drought tolerance in potato genotypes.

The Soil Water Balance model (SWB) was calibrated for the cultivar Up-to-date, using autumn planting data sets from earlier studies. SWB generally performed satisfactorily with regard to the simulation of dry matter production and water deficit of the soil profile for both well-watered and water-stressed conditions in autumn seasons. Simulations of crop growth and soil-water depletion were, however, not accurate in spring plantings if the crop parameters determined for autumn plantings were used. Canopy size was underestimated and the date of senescence was too early, resulting in incorrectly simulated soil-water deficits. The reason for the poor results in spring plantings is probably attributable to the fact that the effects of photoperiod and high temperatures on development and assimilate distribution is not taken into account by the generic crop model. The model therefore needs further refinement to ensure better simulations of canopy development over seasons, possibly by accommodating the effect of day-length on growth, development and senescence. Alternatively, separate crop parameters should be determined for spring or summer plantings.

Crop parameters should also be established for cultivars of other maturity classes, which will require complete growth analysis studies. The model should be a valuable irrigation scheduling tool to both advisors and potato producers.

Two of the objectives set for this study were not fully achieved. Firstly, the water requirements for optimal production of different genotypes did not differ within the same maturity class, possibly due to the equal amounts of water applied to all the genotypes in the same rain shelter. It is not known whether the calculated water use of genotypes would have been the same if different irrigation criteria had been adopted, another method of irrigation was used instead of the irrigation boom, or if measurements had allowed for quantification of drainage losses. Secondly, the effects of water stress imposed in different growth stages on growth and development, and therefore the identification of critical growth stages, could not be determined. The irrigation system used (boom) did not permit the imposition of different levels of water stress in different growth stages. A literature study was conducted to establish the current state of knowledge in this regard, which is discussed in Chapter 2.

Recommendations for future water-use studies on potatoes include the following: if the water requirements of individual genotypes are to be established, the irrigation boom system should deliberately not be used, for the reasons already elaborated in this section. These also apply to studies for determining the effect of water levels on tuber internal quality. The irrigation boom is, however, ideal when genotypes are to be screened for drought tolerance. The suitability of photosynthetic rate and stomatal resistance as early screening methods for drought tolerance should be evaluated on independent data sets before being applied. The SWB irrigation scheduling model should be refined to enable its use in any season. Crop parameters should also be established for potato cultivars of other maturity classes.

The technology transfer actions that have already taken place include the paper presentations, lectures and popular publications listed in Appendix A. This study forms the basis of a Ph.D. dissertation by the senior author and several scientific publications are to follow within the next year. A workshop is planned for the second half of 1997 in conjunction with the Potato Producers' Organisation. The purpose of the workshop will be to inform major role players in the potato industry on the most important research results and the conclusions drawn from the study. The SWB model calibrated as part of this study will also be demonstrated at the workshop.

LITERATURE CITED

ADAMS, S.S. & STEVENSON, W.R., 1990. Water management, disease development, and potato production. Potato management symposium papers. 67,3-11.

ANNANDALE, J.G. & STOCKLE, C.O., 1994. Fluctuation of evapotranspiration crop coefficients with climate: A sensitivity analysis. *Irrig. Sci.* 15, 1-7.

ANNANDALE, J.G., VAN DER WESTHUIZEN, A.J. & OLIVIER, F.C., 1996. Die fasilitering van tegnologie oordrag deur verbeterde besproeiingsriglyne vir groente en 'n meganistiese gewasmodeleringsbenadering. WNK Verslag No 476/1/96, Pretoria.

BANSAL, K.C. & NAGARAJAN, S., 1986. Leaf water content, stomatal conductance and proline accumulation in leaves of potato (*Solanum tuberosum* L.) in response to water stress. *Ind. J. Plant Physiol.* 29(4), 397-404.

BARRAGAN, J. & RECASENS, I., 1988. Irrigation experiment using a line-source sprinkler system. *Acta Hort.* 228, 83-89.

BENADE, N., ANNANDALE, J.G. & HESTER VAN ZIJL, 1996. The development of a computerized management system for irrigation schemes. WRC Report no 513/1/95.

BHAGSARI, A.S., WEBB, R.E., PHATAK, S.C. & JAWORSKI, C.A.,1988. Canopy photosynthesis, stomatal conductance and yield of *Solanum tuberosum* grown in a warm climate. *Am. Potato J.* 65, 393-407.

BODLAENDER, K.B.A., 1986. Effects of drought on water use, photosynthesis and transpiration of potatoes. 1. Drought resistance and water use. In: Potato Research of tomorrow. Eds. A.G.M. Beekman *et al.* Pudoc: Wageningen.

BOX, J.E. & RAMSEUR, E.L., 1993. Minirhizotron wheat root data: Comparisons to soil core root data. *Agron. J.* 85, 1058-1060.

BRESLER, E., DAGAN, G., & HANKS, R.J., 1982. Statistical analysis of crop yield under controlled line-source irrigation. *Soil Sci. Soc. Am.J.* 46, 841-847.

BRISTOW, K.B. & CAMPBELL, G.S., 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agric. For. Meteor.* 31, 159-166.

BROWN, J., MACKAY, G.R., BAIN, H., GRITTITH, D.W. & ALLISON, M.J.,1990. The processing potential of tubers of the cultivated potato, *Solanum tuberosum* L., after storage at low temperatures. *Potato Res.* 33, 219-227.

BURGERS, M.S. & NEL, P.C., 1984. Potato irrigation scheduling and straw mulching. *S. Afr. J. Plant Soil.* 1(4), 111-116.

CALDIZ, D.O., 1991. Influence of origin and storage system on physiological age, crop growth and yield of seed potato. *Ind. J. Agric. Sci.* 61(1), 1-6.

CAMPBELL, G.S. & DIAZ, R., 1988. Simplified soil water balance model to predict crop transpiration. In: Drought research priorities. Eds. F.R. Bidinger & C. Johanson.

CAMPBELL, G.S. & STOCKLE, C.O., 1993. Prediction and simulation of water use in agricultural systems. In: International Crop Science. 1. CSSA, Madison.

CHAN, K.Y., & MEAD, J.A., 1992. Tillage-induced differences in the growth and distribution of wheat-roots. *Aust. J. Agric. Res.* 43, 19-28.

CEULEMANS, R., IMPENS, I., LAKER, M.C., VAN ASSCHE, F.M.G. & MOTTRAM, R., 1988. Net CO_2 exchange rate as a sensitive indicator of plant water status in corn (*Zea mays* L.). *Can. J. Sci.* 68, 597-606.

CHAUDHURI, U.N., DEATON, M.L., KANEMASU, E.T., WALL, G.W., MACRARIAN, V. & DOBRENZ, A.K., 1986. A procedure to select drought-tolerant sorghum and millet genotypes using canopy temperature and vapour pressure deficit. *Agron. J.* 78, 490-494.

COLEMAN, W.K., 1986. Water relations of the potato (*Solanum tuberosum* L.) cultivars Raritan and Shepody. *Am. Potato J.* 63, 263-276.

COLEMAN, W.K., TAI, G.C.C., CLAYTON, S., HOWIE, M. & PEREIRA, A., 1993. A portable monitor for the rapid assessment of processing quality of stored potato tubers. *Am. Potato J.* 70, 909-923.

COLES, G.D., LAMMERINK, J.P. & WALLACE, A.R., 1993. Estimating potato crisp colour variability using image analysis and a quick visual method. *Potato Res.* 36, 127-134.

COTHER, E.J., HOCKING, D. & LOGAN, B.J., 1981. Potato production in a semi-arid environment: agronomy, pathology and Riverina region of New South Wales, Australia. Technical Bulletin 25 Department of Agriculture, New South Wales. 1-36.

DE JAGER, J.M., 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA.* 20 (4), 307-314.

DEMAGANTE, A.L., HARRIS, P.M. & ZAAG, VAN DER, P.V, 1995. A promising method for drought tolerance in potato using apical cuttings. *Am. Potato J.* 72, 577-588.

DOGRAS, C., SIOMOS, A. & PSOMAKELIS, C., 1991. Sugar content and dry matter in potatoes stored under fluctuating temperatures in non-refrigerated stores in Greece. *Potato Res.* 34, 389-396.

DOORENBOS, J. & KASSAM, A.H., 1979. Yield response to water. FAO Irrigation and drainage paper 33. Rome.

DWELLE, R.B., KLEINKOPF, G.E. & PAVEK, J.J., 1981. Stomatal conductance and gross photosynthesis of potato (*Solanum tuberosum* L.) as influenced by irradiance, temperature and growth stage. *Potato Res.* 24, 49-59.

DWELLE, R.B., KLEINKOPF, G.E., STEINHORST, R.K., PAVEK, J.J. & HURLEY, P.J., 1981. The influence of physiological processes on tuber yield of potato clones (*Solanum tuberosum* L.): Stomatal diffusive resistance, stomatal conductance, gross photosynthetic rate, leaf canopy, tissue nutrient levels, and tuber enzyme activities. *Potato Res.* 24, 33-47.

DWELLE, R.B., 1985. Chapter 2. Photosynthesis and Photo assimilate Partitioning. In: Potato Physiology. Ed. P.H. Li. Academic Press Inc. Ltd. London.

EKANAYAKE, I.J., & MIDMORE, D.J., 1992. Genotypic variation for root pulling resistance in potato and its relationship with yield under water-deficit stress. *Euphytica.* 61, 43-53.

EWING, E.E., SENESAC, A.H. & SIECZKA, J.B., 1981. Effects of short periods of chilling and warming on potato sugar content and chipping quality. *Am. Potato J.* 58, 633-647.

EZEKIEL, R., PERUMAL, N.K. & SUKUMARAN, N.P., 1987. Diurnal changes in net photosynthetic rate of potato cultivars in the field. *Photosynthetica.* 21(4), 579-583.

EZEKIEL, R., PERUMAL, N.K. & SUKUMARAN, N.P., 1989. Stomatal density, stomatal resistance and photosynthetic rate in potato cultivars. *Photosynthetica* 23(4), 671-673.

FERNANDEZ, G.C.J., 1991. Repeated measure analysis of line-source sprinkler experiments. *Hort. Sci.* 26(4), 339-342.

FISCHER, R.A. & MAUER, R., 1978. Drought resistance in spring wheat cultivars. I. Grain yield response. *Austr. J. Agr. Res.* 29, 897-907.

FLETCHER, H.F.& MAURER, A.R., 1966. A movable rain shelter for small experimental plots. *Can. J. Plant Sci.* 46, 695-698.

FULTON, J.M., 1970. Relationship of root extension to the soil moisture level required for maximum yield of potatoes, tomatoes and corn. *Can. J. Soil Sci.* 50, 92-94.

GARROT, D.J., OTTMAN, M.J., FRANGMEIER, D.D. & HUSMAN, S.H., 1994. Quantifying wheat water stress with the crop water stress index to schedule irrigations. *Agron. J.* 86, 195-199.

GAWAD, A.A., OMER, E.A. & AHMED, S.S., 1990. Effect of storage on the glycoalkaloid and carbohydrate contents in different potato varieties. 23rd International Horticultural Congress. (27 Aug - 1 Sept. 1990) Firenze, Italy, 703-707.

GRAEME, D., COLES, J., LAMMERIK, P. & WALLACE, A.R., 1993. Estimating potato crisp colour variability using image analysis and a quick visual method. *Potato Res.* 36, 127-134.

GREEN, G.C., 1985. Estimated irrigation requirements of crops in South Africa. Memoirs on the agricultural natural resources of South Africa. No 1. Soil and Irrigation Research Institute. Dept. Agriculture and water supply, Pretoria.

HANKS, R.J., KELLER, J., RASMUSSEN, V.P. & WILSON, G.D., 1976. Division S-6-Soil and water management and conservation. *Soil Sci. Soc. Am. J.* 40, 426-429.

HANKS, R.J., SISSON, D.V., HURST, R.L. & HUBBARD, K.G., 1980. Statistical analysis of results from irrigation experiments using the line-source sprinkler system. *Soil Sci. Soc. Am. J.* 44, 886-888.

HARRIS, G.A., & CAMPBELL, G.S., 1989. Automated qualification of roots using a simple image analyser. *Agron. J.* 81, 935-938.

HARTZ, T.K. & MOORE, F.D., 1978. Prediction of potato yield using temperature and insolation data. *Am. Potato J.* 55, 431-436.

HARRIS, P.M., 1978. The Potato Crop. A scientific basis for improvement. London

HAVERKORT, A.J., VAN DER WAART, M. & BODLAENDER, K.B.A., 1990. The effect of early stress on numbers of tubers and stolons of potato in controlled and field conditions. *Potato Res.* 33, 89-96.

INCERTI, M. & O'LEARY, G.J., 1990. Rooting depth of wheat in the Victorian Mallee. *Austr. J. Exp. Agric.* 30, 817-824.

IRITANI, W.M. & WELLER, L.D., 1977. Changes in sucrose and reducing sugar contents of Kennebec and Russet Burbank tubers during growth and post-harvest holding temperatures. *Am. Potato J.* 54, 395-404.

IRITANI, W.M., 1981. Growth and preharvest stress and processing quality of potatoes. *Am. Potato J.* 58, 71-80.

JEFFERIES, R.A. & MACKERRON, D.K.L., 1987. Aspects of the physiological basis of cultivar differences in yield of potato under droughted and irrigated conditions. *Potato Res.* 30, 201-217.

JEFFERIES, R.A., 1989. Water-stress and leaf growth in field-grown crops of potato (*Solanum tuberosum* L.). *J. Exp. Bot.* 40 (221), 1375-1381.

JEFFERIES, R.A., HEILBRONN, T.D. & MACKERRON, D.K.L., 1989. Estimating tuber dry matter concentration from accumulated time and soil moisture. *Potato Res.* 32, 411-417.

JEFFERIES, R.A., 1993. Responses of potato genotypes to drought. I. Expansion of individual leaves and osmotic adjustment. *Ann. Appl. Biol.* 122, 93-104.

JEFFERIES, R.A. & MACKERRON, D.K.L., 1993. Responses of potato genotypes to drought. II. Leaf area index, growth and yield. *Ann. Appl. Biol.* 122, 105-112.

JEWELL, S., & STANLEY, R., 1989. The influence of defoliation date and harvest on the quality of potatoes for french fry production. *Potato Res.* 32, 431-438.

JOHNSON, K.B., CONLON, R.L., NELSON, D.C., ROUSE, D.I. & TENG, P.S., 1988. Validation of a simple potato growth model in the North Central United States. *Am. Potato J.* 65, 27-44.

KINCAID, D.C., WESTERMANN, D.T. & TROUT, T.J., 1993. Irrigation and soil temperature effects on Russet Burbank quality. *Am. Potato J.* 70, 711-722.

KOOMAN, P.L. & HAVERKORT, A.J., 1995. Modelling development of growth of the potato crop influenced by temperature and day length: LINTUL-POTATO. In: Potato Ecology and modelling of crops under conditions limiting growth. Eds. A.J. Haverkort & D.K.L. MacKerron. Kluwer Academic Publishers: Dordrecht.

KRUSE, E.G., ELLS, J.E. & McSAY, A.E., 1990. Scheduling irrigations for carrots. *Hort. Science*. 25(6), 641-644.

KVIEN, C.S., & BRANCH, W.D., 1988. Design and use of a fully automated portable rain shelter system. *Agron. J.* 80, 281-283

LARSEN, D.C., 1984. Simplifying potato irrigation scheduling - the Idaho program. *Am. Potato J.* 61, 215-227.

LEMAGA, B. & CAESAR, K., 1990. Relationships between numbers of main stems and yield components of potato (*Solanum tuberosum* L. cv. Erntestolz) as influenced by different daylenghts. *Potato Res.* 33, 257-267.

LESKOVAR, D.I. & CANTLIFFE, D.J., 1989. Pepper (*Capsicum annuum* L.) root growth and its relation to shoot growth in response to nitrogen. *J. Hort. Sci.* 64, 711-716.

LEVY, D., 1983a. Varietal differences in the response of potatoes to repeated short periods of water stress in hot climates. I. Turgor maintenance and stomatal behaviour. *Potato Res.* 26, 303-313.

LEVY, D., 1983b. Varietal differences in the response of potatoes to repeated short periods of water stress in hot climates. 2. Tuber yield and dry matter accumulation and other tuber properties. *Potato Res.* 26, 315-321.

LEVY, D., GENIZI, A. & GOLDMAN, A., 1990. Compatibility of potatoes to contrasting seasonal conditions, to high temperatures and to water deficit: The association with time of maturation and yield potential. *Potato Res.* 33, 325-334.

LOGAN, B.J., 1989. Effect of irrigation and nitrogen on yield and quality of potatoes grown in semi-arid South Western N.S.W. *Acta Hort.* 247, 243-24

LYNCH, D.R. & KOZUB, G.C., 1993. Effect of canopy size and shape on the tuber yield of sixteen potato genotypes. *Ann. appl. Biol.* 123, 93-103.

MACKERRON, D.K.L. & WAISTER, P.D., 1985. A simple model of potato growth and yield. *Agric. Forest. Meteor.* 34, 241-252.

MACKERRON, D.K.L. & JEFFERIES, R.A., 1988. The distributions of tuber sizes in droughted and irrigated crops of potato. I. Observations on the effect of water stress on graded yields from differing cultivars. *Potato Res.* 31, 269-278.

MACKERRON, D.K.L., 1989. Quantified responses of the potato crop to water-stress. Potato Research Symposium. Warmbaths, South Africa.. 1-5pp.

MAHALAKSHMI, V., BIDINGER, F.R. & RAO, G.D.P., 1990. Line-source vs. irrigated/nonirrigated treatments for evaluation of genotype drought response. *Agron. J.* 82, 841-844.

MARUTANI, M. & CRUZ, F., 1989. Influence of supplemental irrigation on development of potatoes in the tropics. *Hort. Science.* 24(6), 920-923.

MILLER, D.E. & MARTIN, M.W., 1987a. The effect of irrigation regime and subsoiling on yield and quality of three potato cultivars. *Am. Potato J.* 64, 17-25.

MILLER, D.E. & MARTIN, M.W., 1987b. Effect of declining or interrupted irrigation on yield and quality of three potato cultivars grown on sandy soil. *Am. Potato J.* 64, 109-117.

MILLER, D.E. & MARTIN, M.W., 1990. Responses of three early potato cultivars to subsoiling and irrigation regime on a sandy soil. *Am. Potato J.* 67, 769-777.

MOLL, A., 1983. Photosynthetic rate and yield of potato clones. *Potato Res.* 26, 191-202.

MOULD, R.D.& RUTHERFOORD, R.J., 1980. The effect of moisture stress during consecutive growth stages on tuber yield and quality of BP1 potatoes (*Solanum tuberosum* L.) *Crop Production*. 9, 89-95.

MUNNS, R. & PEARSON, C.P., 1974. Effect of water deficit on translocation of carbohydrate in *Solanum tuberosum*. *Austr. J. Pl. Physiol.* 1, 529-537.

NORTJE, P.F., 1988. The effects of soil moisture regimes on water use, yield and quality of cabbage and carrots. Ph.D. thesis, University of the Orange Free State, Bloemfontein.

OJALA, J.C., STARK, J.C. & KLEINKOPF, G.E., 1990. Influence of irrigation and nitrogen management on potato yield and quality. *Am. Potato J.* 67, 29-43.

OOSTERHUYS, D.M. & WALKER, S., 1987. Stomatal resistance measurement as an indicator of water deficit stress in wheat and soybeans. *S. Afr. J. Plant Soil.* 4(3), 113-120.

ORR, P.H. & JANARDAN, K.G., 1990. A procedure to correlate color measuring systems using potato chip samples. *Am. Potato J.* 67, 647-654.

OWINGS, T.R., IRITANI, W.M. & NAGEL, C.W., 1978. Respiration rates and sugar accumulation in normal and stressed Russet Burbank potatoes. *Am. Potato J.* 55, 211-220.

PENNYPACKER, B.W., LEATH, K.T., STOUT, W.L. & HILL, R.R., 1990. Technique for simulating field drought stress in the greenhouse. *Agron. J.* 82, 951-957.

PIETERSE, B.J., 1994. Fisiologiese veroudering van aartappelmoere. Ph.D. thesis. University of Pretoria, Pretoria.

POTATO PRODUCERS' ORGANISATION ANNUAL REPORT, 1995. PPO, Pretoria.

PRICE, M., JALALUDDIN, M.D. & DILDAY, R.H., 1992. Evaluation of rice germplasm for drought tolerance. As quoted by F.T. Rossouw and J. Waghmarae. *S. Afr. J. Sci.* 91, 149-150.

RICHARDSON, D.L., DAVIES, H.V. & ROSS, H.A., 1990a. An investigation into the factors influencing sugar levels in UK grown potatoes (cv. Record). *Potato Res.* 33, 235-239.

RICHARDSON, D.L., DAVIES, H.V. & ROSS, H.A., 1990b. Potato tuber sugar content during development and storage (10 °C): possible predictors of storage potential and the role of sucrose in storage hexose accumulation. *Potato Res.* 33, 241-245.

ROBINSON, J.M. & HUBBARD, K.G., 1990. Soil water assessment model for several crops in the high plains. *Agron. J.* 82, 1141-1148.

ROSSOUW, F.T. & WAGHMARAE, J., 1995. The effect of drought on growth and yield of two South African potato cultivars. *S. Afr. J. Sci.* 91, 149-150.

RUTHERFOORD, R.J. & DE JAGER, J.M., 1975. Water status and stomatal behaviour of BP1 potatoes (*Solanum tuberosum* L.) and their effect upon yield. *Crop Production.* 4, 125-128.

SCANLON, M.G., ROLLER, R., MAZZA, G. & PRITCHARD, M.K., 1994. Computerized video image analysis to quantify color of potato chips. *Am. Potato J.* 71, 717-733.

SCHAPENDONK, A.H.C.M., SPITTERS, C.J.T.& GROOT, P.J., 1989. Effects of water stress on photosynthesis and chlorophyll fluorescence of five potato cultivars. *Potato Res.* 32, 17-32.

SHIMSHI, D., SHALHEVET, J. & MEIR, T, 1983. Irrigation regime effects on some physiological responses of potato. *Agron. J.* 75, 262-268.

SHOCK, C.C., HOLMES, Z.A., STIEBER, T.D., ELDREDGE, E.P. & ZHANG, P., 1993. The effect of timed water stress on quality, total solids and reducing sugar content of potatoes. *Am. Potato J.* 70, 227-241.

SINGH, M., RAO, R.C.N. & WILLIAMS, J.H., 1991, A statistical assessment of genotypic sensitivity of groundnut (*Arachis hypogae* L.) to drought in line source sprinkler experiments. *Euphytica.* 57, 19-25.

SMITH, M., 1992. Expert consultation on revision of FAO methodologies for crop water requirements. FAO Report, Rome.

SOWOKINOS, J., 1990. Effect of stress and senescence on carbon partitioning in stored potatoes. *Am. Potato J.* 67, 849-857.

SPITTERS, C.J.T., NEELE, A.E.F. & SCHAPENDONK, A.H.C.M., 1988. Crop physiological components of tuber yield and their use in potato breeding. As quoted by R.A. Jefferies and D.K.L. MacKerron. *Ann. Appl. Biol.* 122, 105-112.

SPITTERS, C.J.T. & SCHAPENDONK, A.H.C.M., 1990. Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. *Plant Soil.* 123, 193-203.

STALHAM, M.A & ALLEN, E.J., 1993. Effect of irrigation regime on rooting density of contrasting cultivars. Abstracts of the 12th Triennial Conference of the EAPR. 186-187pp. Paris, France.

STARK, J.C., 1987, Stomatal behaviour of potatoes under nonlimiting soil water conditions. *Am. Potato J.*, 64, 301-309.

STEYN, J.M., DU PLESSIS, H.F. & NORTJE, P.F., 1992. Die invloed van verskillende waterregimes op Up-to-date aartappels. II. Opbrengs, grootteverspreiding, kwaliteit en waterverbruik. *S. Afr. J. Plant Soil.* 9(3), 118-122.

STRUIK, P.C. & VAN VOORST, G., 1986, Effects of drought on the initiation, yield, and size distribution of tubers of *Solanum tuberosum* L. cv. Brintje. *Potato Res.* 29, 487-500.

SUKUMARAN, N.P., EZEKIEL, R. & PERUMAL, N.K., 1989. Response of net photosynthetic rate and stomatal conductance to water deficit in different potato cultivars. *Photosynthetica.* 23(4), 664-666.

SUSNOSCHI, M. & SHIMSHI, D., 1985. Growth and yield studies of potato development in a semi-arid region. 2. Effect of water stress and amounts of nitrogen top dressing on growth of several cultivars. *Potato Res.* 28, 161-176.

TAN, C.S. & FULTON, J.M., 1985. Water uptake and root distribution by corn and tomato at different depths. *Hort Science.* 20(4), 686-688.

TANNER, C.B., 1981. Transpiration efficiency of potato. *Agron. J.* 73, 59-64.

TANNER, C.B., & SINCLAIR, T.R., 1993. Efficient water use in crop production: Research or re-search? In: Limitations to efficient water use in crop production. Eds. H.M. Taylor, W.R. Jordan & T.R. Sinclair. SSSA Publication, Madison, USA.

TREBEJO, I., & MIDMORE, D.J., 1990. Effect of water stress on potato growth, yield and water use in a hot and cool tropical climate. *J. Agric. Sci.* 114, 321-334.

UPCHURCH, D.R., RITCHIE, J.T. & FOALE, M.A., 1983. Design of a large dual-structure rainout shelter. *Agron. J.* 75, 845-848.

VAN DER MESCHT, A., DE RONDE, J.A. & ROSSOUW, F.T., 1992. Specific DNA binding of a 38 kDa polypeptyde during drought stress in potato. *J. S. Afr. Soc. Hort. Sci.* 2, 92-95.

VAN LOON, C.D., 1981. The effect of water stress on potato growth, development and yield. *Am. Potato J.* 58, 51-69.

VAN LOON, C.D., 1986. Drought, a major constraint to potato production and possibilities for screening for drought resistance. In: Potato research of tomorrow. Eds. A.G.B. Beekman *et al.* Proceedings of International Seminar, Wageningen, Netherlands, Pudoc: Wageningen.

VAN HEEMST, D.J., 1986. The distribution of dry matter during growth of a potato crop. *Potato Res.* 29, 55-66.

VOS, J. & GROENWOLD, J., 1988. Water relations of potato leaves. I. Diurnal changes, gradients in the canopy, and effects of leaf-insertion number, cultivar and drought. *Annals of Botany.* 62, 363-371.

VOS, J. & GROENWOLD, J., 1989. Characteristics of photosynthesis and conductance of potato canopies and the effects of cultivar and transient drought. *Field Crops Res.* 20, 237-250.

WILCOX, D.A. & ASHLEY, R.A., 1982. The potential use of plant physiological responses to water stress as an indication of varietal sensitivity to drought in four potato (*Solanum tuberosum* L.) varieties. *Am. Potato J.* 59, 533-545.

WILCOX-LEE, D., 1990. Effect of soil on growth, water relations and photosynthesis in an open-pollinated and male hybrid asparagus cultivar. *Acta Hort.* 271, 457-465.

WILLMOT, C.J., 1982. Some comment on the evaluation of model performance. *Bull. of Am. Meteorol. Soc.* 64, 1309-1313

WOLF, S., OLESKINSKI, A.A., RUDICH, J. & MARANI, A., 1990. Effect of high temperature on photosynthesis in potatoes. *Annals of Botany.* 65, 179-185.

WOLF, S., 1993. Effect of leaf on photosynthesis, carbon transport and carbon allocation in potato plants. *Potato Res.* 36, 253-262.

YAU, S.K., 1995. Regression and AMMI analyses of genotype X environment interactions: An empirical comparison. *Agron. J.* 87, 121-126.

ZELITCH, I., 1975. Improving the efficiency of photosynthesis. *Science.* 188, 626-633.

APPENDIX A

TECHNOLOGY TRANSFER ACTIONS THAT EMANATED FROM THE RESEARCH PROJECT:

1. Papers presented at scientific conferences:

STEYN, J.M. & DU PLESSIS, H.F., 1993. 'n Evaluasie van die droogteverdraagsaamheid van Suid-Afrikaanse aartappelcultivars. SA Society for Crop Production (SASCP) Congress. Rustenburg, South Africa.

DU PLESSIS, H.F. & STEYN, J.M., 1993. Fotosintesetempo van aartappelcultivars soos beïnvloed deur tekortbesproeiing. SASCP Congress. Rustenburg, South Africa.

STEYN, J.M. & DU PLESSIS, H.F., 1993. Evaluation of the drought resistance of three potato cultivars in South Africa. European Association for Potato Research (EAPR) Triennial Conference. Paris, France.

STEYN, J.M. & DU PLESSIS, H.F., 1996. Production, water use and drought tolerance of two new potato genotypes. SASCP Congress. Bloemfontein, South Africa. (The D.F. Retief trophy for the best paper by a young scientist was presented to the senior author for this paper).

STEYN, J.M. & ANNANDALE J.G., 1996. Soil Water Balance: A generic model suitable for the irrigation scheduling of potatoes. EAPR Triennial Conference. Veldhoven, The Netherlands.

STEYN, J.M. & ANNANDALE J.G., 1997. Irrigation scheduling of potatoes using the Soil Water Balance model. First All Africa Crop Science Congress, Pretoria.

2. Poster presented at scientific conferences:

STEYN, J.M. & DU PLESSIS, H.F., 1994. An evaluation technique for drought tolerance in potatoes. SASCP Congress. Cedara, South Africa.

3. Popular publications:

STEYN, J.M., 1993. Doeltreffende watervoorsiening kan aartappelopbrengste verdubbel. Roodeplaat Bulletin 38, 6-7.

MARTIN STEYN & HENNIE DU PLESSIS, 1995. Nuwe cultivars presteer in droogte. Roodeplaat Bulletin 41, 18.

FLIP STEYN & MARTIN STEYN, 1995. Die effek van waterstremming op die aartappelplant. Chips, 9, 3, 27.

MARTIN STEYN, HENNIE DU PLESSIS & PIERRE FOURIE, 1995. Nuwe cultivars presteer in droogte. Chips, 9, 4, 39.

4. Lectures presented on courses and information days:

STEYN, J.M., 1993. Waterbehoeftes en besproeiingskedulering van aartappels. Potato Short Course. Citrusdal, South Africa.

STEYN, J.M., 1995. Waterbehoeftes van aartappels. Information day. Louwna, South Africa.

STEYN, J.M., 1996. Die verbouing, water- en voedingsbehoeftes van aartappels. Potato cultivation course. Tolwe, South Africa.

STEYN, J.M., 1996. The cultivation and irrigation of potatoes. Vegetable Course. Roodeplaat, South Africa.

5. Radio talks

MARTIN STEYN, 1996. Besproeiingskedulering en modellering van aartappels - report on a visit to the Cambridge University, United Kingdom.

6. Post-graduate studies

STEYN, J.M., 1997 (D.V.). Response of potato genotypes to different water regimes. Ph.D. Thesis, University of Pretoria.

APPENDIX B

TABLE B1: Summary of ANOVA table for AMMI: The influence of different water regimes on tuber yield of six potato genotypes during the 1992 autumn planting

Source	df	Mean sum of squares	Probability level	
Treatment	29	647.64	0.0000	***
Genotype	5	255.25	0.0000	***
Water	4	4289.43	0.0000	***
Genotype X water	20	17.38	0.8694	NS
IPCA 1	8	30.38	0.3552	NS
Residual	12	8.71	0.9836	NS
Error	90	27.04		
Total	119	178.28		

TABLE B2: Marketable tuber yield (Mg ha^{-1}) of late-maturity potato genotypes as influenced by different water regimes and plantings

Year	Planting	Genotype name	Water regime				
			W1	W2	W3	W4	W5
1992	Spring	Vanderplank	46.0	41.1	31.1	19.6	9.0
		Up-to-date	53.4	59.3	32.9	15.3	3.4
		Late Harvest	47.4	46.6	38.3	28.0	9.8
1993	Autumn	Vanderplank	42.2	41.9	28.1	22.1	11.2
		Up-to-date	54.2	49.5	39.4	31.6	15.3
		Late Harvest	53.6	52.1	43.1	32.7	16.9
1993	Spring	Late Harvest	53.0	42.5	37.3	26.7	8.8
		Hoëvelder	63.4	54.4	38.0	28.0	6.8
		Mnandi	66.3	64.6	47.2	34.5	12.0
1994	Autumn	Late Harvest	56.2	44.8	41.2	26.6	17.0
		Hoëvelder	56.1	43.9	36.4	25.8	16.9
		Mnandi	66.4	49.1	42.0	28.6	16.2
1994	Spring	Late Harvest	49.4	51.2	44.0	34.0	13.1
		81-163-40	57.7	48.5	47.5	30.5	3.6
		83-363-67	59.9	58.1	46.4	33.5	8.4
1995	Autumn	Late Harvest	31.3	26.9	21.9	20.1	17.1
		81-163-40	37.4	30.1	26.2	23.3	18.9
		83-363-67	30.5	23.7	20.5	17.8	13.2

TABLE B3: Marketable tuber yield (Mg ha^{-1}) of medium-maturity potato genotypes as influenced by different water regimes and plantings

Year	Planting	Genotype name	Water regime				
			W1	W2	W3	W4	W5
1992	Spring	Vanderplank	46.1	44.8	41.1	28.0	15.9
		Up-to-date	63.6	65.5	54.3	29.5	9.1
		Late Harvest	54.8	53.7	45.5	31.7	12.0
1993	Autumn	Vanderplank	27.4	24.6	27.0	21.6	14.1
		Up-to-date	60.4	59.3	49.1	41.8	31.8
		Late Harvest	53.6	51.3	47.3	36.7	28.3
1993	Spring	Up-to-date	67.1	68.5	51.0	18.9	7.7
		82-252-5	55.2	48.0	35.1	26.8	9.1
		83-252-1	58.1	52.0	36.5	24.8	10.1
1994	Autumn	Up-to-date	50.9	46.1	44.7	41.0	26.7
		82-252-5	53.0	49.0	53.7	45.9	26.4
		83-252-1	47.4	43.6	45.5	43.7	23.1
1994	Spring	Up-to-date	72.1	59.9	42.4	24.5	5.0
		Mondial	67.5	58.6	39.8	21.7	6.1
		84-304-4	44.7	38.9	33.0	20.6	7.7
1995	Autumn	Up-to-date	28.7	24.7	19.4	17.3	17.7
		Mondial	41.9	37.5	29.3	24.5	20.9
		84-304-4	24.9	25.3	19.8	15.8	13.8

TABLE B4: Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different late-maturity potato genotypes during the 1992 - 1994 spring plantings

Source	df	Mean sum of squares	Probability level *	
Treatment	29	0.2793	0.0000	***
Genotype	5	0.5726	0.0000	***
Water	4	0.7319	0.0000	***
Genotype X water	20	0.1155	0.0357	*
IPCA 1	8	0.1900	0.0063	**
Residual	12	0.0658	0.4155	NS
Error	59	0.0625		
Total	88	0.1339		

* NS : not significant

TABLE B5: Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different late-maturity potato genotypes during the 1993 - 1995 autumn plantings

Source	df	Mean sum of squares	Probability level	
Treatment	29	0.0672	0.0014	**
Genotype	5	0.3282	0.0000	***
Water	4	0.0334	0.3046	NS
Genotype X water	20	0.0087	0.9966	NS
IPCA 1	8	0.0144	0.8276	NS
Residual	12	0.0049	0.9987	NS
Error	60	0.0270		
Total	89	0.0401		

TABLE B6: **Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different medium-maturity potato genotypes during the 1992 - 1994 spring plantings**

Source	df	Mean sum of squares	Probability level *	
Treatment	24	0.6832	0.1683	NS
Genotype	4	0.2390	0.7485	NS
Water	4	2.9363	0.0006	***
Genotype X water	16	0.2310	0.9519	NS
IPCA 1	7	0.4999	0.4366	NS
Residual	9	0.0218	0.9999	NS
Error	49	0.4954		
Total	73	0.5572		

* NS : *not significant*

TABLE B7: **Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different medium-maturity potato genotypes during the 1993 - 1995 autumn plantings**

Source	df	Mean sum of squares	Probability level	
Treatment	29	0.2658	0.0000	***
Genotype	5	1.4197	0.0000	***
Water	4	0.0922	0.0019	**
Genotype X water	20	0.0120	0.8755	NS
IPCA 1	8	0.0233	0.3047	NS
Residual	12	0.0045	0.9956	NS
Error	60	0.0192		
Total	89	0.0995		

RESPONSE OF POTATO GENOTYPES TO DIFFERENT IRRIGATION WATER REGIMES

by

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with specific reference to potatoes"

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EXECUTIVE SUMMARY

The potato is an important source of food world wide. In South Africa the crop is primarily produced under irrigation (about 73% of the total area under potatoes) for the fresh market, for the processing industry as chips and crisps, and for seed potatoes.

In subtropical climates potato crops are often subjected to unfavourable conditions of high temperatures and water shortages during the growing season: heat- and water stress adversely affect growth, tuber yield and quality. In these hot, dry climates the high evaporative demand increases crop water requirements, which may compound the sensitivity of the crop to water stress, resulting in greater yield reductions than experienced with similar water deficits under cooler conditions.

Due to limited water resources and unreliable annual distribution of rain, water stress is a major constraint on potato production in South Africa. In some production areas the quantity and quality of water resources have deteriorated badly due to over exploitation. Two possible approaches could be followed by agriculture to achieve savings on water use without reducing the cultivated area. The first option is to cut down on current water use by the application of sound irrigation scheduling techniques as it has been shown that, although water stress is considered an important production limiting factor, only a few producers apply scheduling on irrigated crops. The negative attitude towards irrigation scheduling can be attributed to various factors. The lack of easy, quick and reliable scheduling methods seems to be one of the major reasons. The second option is to breed and select genotypes that are more efficient with regard to water use characteristics, which may be a long term solution to the problem. This alternative is well recognized for many crops and breeding for better adaptability to drought is an important objective of the local potato breeding programme at Roodeplaat.

Since little is known about the amounts of water required for optimum production and the effects of water stress on local potato genotypes, the following objectives were set to clarify these aspects:

1. To determine the water use of the most important potato cultivars and breeding lines to ensure maximum yield and quality.
2. To identify the critical growth stages of potatoes to water stress.
3. To determine the effect of water stress imposed in different growth stages on growth and development.
4. To determine the suitability of some physiological parameters to indicate the existence of plant water stress and to serve as early screening methods for drought tolerance in potato genotypes.
5. To use collected data for the development of crop growth models and adapt irrigation scheduling models for potatoes.

Seven trials were conducted from the 1992 autumn planting until the autumn of 1995. The trials were planted under automated rain shelters and irrigation booms were used in combination with rain shelters.

Genotypic yield differences in response to levels of water stress were mainly confined to the spring plantings, when temperatures and the atmospheric evaporative demand are higher than in autumn. Some genotypes were clearly more adapted to water-stress conditions than others. Of the late genotypes Late Harvest and Mnandi performed best at the dry treatments, while Mnandi had the highest yields at the wetter treatments as well. The findings of this study contrast the suggestions of Jefferies & MacKerron (1993) that there is limited capacity for improved drought tolerance through breeding other than improving the yield potential. Genotypes such as Late Harvest, Vanderplank, 82-252-1 and 83-252-1 had low yield potentials under favourable conditions, but had of the highest yields when they were water-stressed.

The ranking of genotypes according to yields attained at different water treatments is an important contribution to the current state of knowledge and will be valuable to producers in assisting them to select genotypes most suitable to their specific growing conditions. The ranking order of genotypes as a result of water treatments only changed in spring plantings, indicating that in autumn genotypes can be selected purely according to yield potential or

specific needs of the end user. If producers have a choice between spring and autumn planting seasons, the range of high-yielding genotypes to select from will be larger for the autumn planting. High yields can usually be expected from autumn plantings, while the saving on irrigation water will be substantial, compared to a spring planting.

Local potato genotypes were for the first time characterised according to drought tolerance. Drought-tolerant genotypes were regarded as those that showed the lowest reduction in tuber yield when exposed to water stress. Mnandi, Late Harvest, Vanderplank, 82-252-5 and 83-252-1 were the most drought tolerant of the genotypes evaluated. Genotypic differences in drought tolerance were less pronounced in autumn, because temperatures and atmospheric evaporative demand were lower. The drought-sensitivity index demonstrated in this study should be a valuable tool to plant breeders for the selection of drought-tolerant parental material in breeding programmes.

The negative effect of water stress on tuber size was most severe in spring plantings, when temperatures and the atmospheric evaporative demand were higher. The yield of medium and especially large tubers were damaged by water stress, but genotypes within the same trial did not respond differently to water stress.

Water regimes apparently had less effect than temperature on tuber internal quality in spring plantings. The effect of water regimes on tuber quality was not clear and, contrary to most reports in literature, no negative effects of water stress on tuber relative density and chip colour could be demonstrated in spring plantings, while chip colour improved as a result of water stress in autumn plantings. Firstly, the contradictory results are possibly attributable to the dominating effects of temperature on tuber quality. Secondly, the irrigation boom method used does not resemble field conditions, due to the regular application of small amounts of water to dry treatments.

Part one of the first objective, which was to determine the water regimes that will ensure maximum yield and quality of different potato genotypes, were only partly reached: although the intermediate regimes (W2 and W3) seemed to provide the most favourable compromise

between highest yield and best quality, genotypic differences could not be identified. The irrigation boom system used is probably to be blamed for the fact that possible genotypic differences could not be found.

Photosynthetic rate (Pn) and stomatal resistance (Rs) were investigated as indicators of drought tolerance. Tuber yields correlated well ($r=0.87$ to $r=0.99$) with seasonal mean values of both these parameters for all the genotypes, but the regression functions that describe these relationships changed for seasons and genotypes. The magnitude of decline in Pn or increase in Rs in response to drought was found to be related to the magnitude of decline in tuber yield. These relationships are, however, not valid for heat-sensitive genotypes such as Up-to-date. These findings may be a significant contribution to early selection techniques for drought tolerance in crops, but the technique should be evaluated on independent data and on a wider range of more diverse material to prove its usefulness.

The objective of finding suitable physiological parameters as indicators of water stress and to serve as early screening methods for drought tolerance in potatoes was reached, since the regression functions obtained from this study can in future be used to estimate the expected yield reduction of a specific genotype, once the reduction in Pn or increase in Rs for that genotype is established.

The vast differences in total water use between plantings and years were mainly as a result of differences in atmospheric evaporative demand. Normalising the water-use data for seasonal vapour pressure deficits narrowed the gap between years, but differences between spring and autumn plantings were still evident for the same genotypes. The reason for the remaining differences should probably be attributed to the fact that evapotranspiration and not transpiration data was used for comparison.

The small differences observed between genotypes in water use can perhaps be explained by the way water use was calculated and by the method of irrigation used. Water use was mainly a function of water applied, as genotypes within the same maturity class received the same amount of water. Since genotypic differences in water use could not be determined with the

irrigation method used, this second part of the first objective was not reached, as we are not sure that genotypic differences in water requirements were not present. The irrigation boom system is therefore not ideal for water use studies, although it is a valuable technique for drought tolerance screening.

Water-use efficiencies were the highest for autumn plantings, because less water was lost through evaporation without contributing to the production of dry matter. Highest water-use efficiencies were generally recorded at the intermediate treatments (W2 and W3) for both plantings. The high-potential cultivars Up-to-date, BP1, Mnandi, 81-163-40 and Mondial had the highest efficiencies in autumn plantings, independent of the water treatment applied, but in spring plantings the water-use efficiencies of genotypes were influenced by water treatments. Generally, Up-to-date, and 83-363-67 had the highest efficiencies at the wet to intermediate treatments, while the more drought-tolerant genotypes Vanderplank, Late Harvest and Mnandi had high efficiencies at all the water treatments in spring plantings. The medium-maturity genotypes 82-252-5 and 83-252-1 had the highest efficiencies at the driest treatments.

Rooting density in deep soil layers was not related to drought tolerance for the genotypes studied. Although root distribution was slightly changed by water regime, root development does not seem to be a suitable indicator of drought tolerance in potato genotypes. The majority of roots were located in the top 600 mm soil layer for all potato genotypes. The greatest portion of soil water was also extracted from this zone, which is suggested as the maximum rooting depth for irrigation scheduling calculations.

The Soil Water Balance model (SWB) was calibrated for the cultivar Up-to-date, using data sets of autumn plantings. SWB generally performed satisfactorily with regard to the simulation of dry matter production and water deficit of the soil profile for both well-watered and water-stressed conditions in autumn plantings. Simulations of crop growth and soil-water depletion were, however, not accurate in spring if the crop parameters determined for autumn plantings were used. Canopy size was under estimated and the date of senescence was too early, resulting in incorrectly simulated soil-water deficits. The reason for the poor results in spring plantings is probably attributable to the fact that the effects of photoperiod and high temperatures on development and assimilate distribution is not taken into account by the generic crop model. The model therefore needs further refinement to ensure better simulations of canopy development over seasons, possibly by accommodating the effect of day-length on growth, development and senescence. Alternatively, separate crop parameters should be determined for spring or summer plantings. Crop parameters should also be established for cultivars of other maturity classes, which will require complete growth analysis studies.

The objective to use data collected in this study for the development or adaptation of a simulation model for irrigation scheduling purposes was reached for the cultivar Up-to-date, a medium-maturity cultivar. Destructive growth analyses were not possible because of the limited number of plants that could be accommodated under the rain shelters. Sufficient crop data were therefore not available for the determination of crop parameters for specific genotypes. If the water requirements of genotypes within the same maturity class do not differ, as suggested by the results of this study, the first important step in future research would be to obtain crop parameters for the most important genotypes belonging to the early and late maturity classes. In spite of the research still needed to improve the model, it should already be a valuable tool which could assist both advisors and potato producers on a daily basis to decide when and how much to irrigate their potato crops.

A part of the first objective was to determine the water requirements for optimal production of different genotypes. The water use of genotypes within the same maturity class did, however, not differ, possibly due to the equal amounts of water applied to all the genotypes for the same water regime. It is therefore not known whether total water use would have been different if another method of irrigation was used instead of the irrigation boom.

The objectives set to determine the effects of water stress imposed in different growth stages on growth and development, and therefore the identification of critical growth stages, were not met in this study. Different levels of water stress could not be imposed at different growth stages, because the irrigation boom did not permit such treatments.

Reports from literature indicate the main effects of drought on growth and development to be the following: Drought usually reduces the canopy size, whereby the interception of solar radiation is reduced. Secondly, crop development and canopy senescence are hastened, which result in a shortened life cycle. Water stress during the tuber initiation phase will result in less tubers being initiated and therefore the potential yield is reduced. The most devastating effect of water stress on tuber yield is during the tuber bulking phase: drought reduces the number of harvestable tubers by reducing the number of tubers that grow into a certain minimum size. The downward shift in tuber size distribution result in a lower total yield.

Water supply may also have adverse effects on tuber internal quality. Tuber relative density and reducing sugar content are the two quality characteristics commonly affected by water supply. Tuber relative density is usually enhanced by water stress late in the growing season, while reducing sugar content will rise as a result of late water stress, resulting in unacceptably dark chip colours.

Recommendations for future water use studies on potatoes include the following: if the water requirements of individual genotypes are to be established, the irrigation boom should deliberately not be used, for the reasons already elaborated on in this section. These also apply to studies for determining the effect of water levels on tuber internal quality. The irrigation boom technique is, however, ideal when genotypes are to be screened for drought tolerance. The suitability of photosynthetic rate and stomatal resistance as early screening methods for drought tolerance should be evaluated on independent data sets before being applied. The SWB irrigation scheduling model should be refined to enable its use in any season. Crop parameters should also be established for potato cultivars of other maturity classes.

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CHAPTER 1

GENERAL INTRODUCTION

The potato is an important source of food in countries world wide. This is also the case in South Africa, where potatoes are the most important vegetable crop. During the 1995 production season for example, potatoes were cultivated on about 56 000 ha (Potato Producers' Organisation (PPO), 1995). About 73% of the potato production area in South Africa is under irrigation. Production is for the fresh market, the processing industry and for seed potatoes.

Potato crops in subtropical climates are often subjected to heat and water stress due to unfavourable conditions of high temperatures and water shortages during the growing season, which adversely affect growth, tuber yield and quality (Coleman, 1986; Levy, Genizi & Goldman, 1990; Miller & Martin, 1990). According to Trebejo & Midmore (1990), in such hot, dry climates the high evaporative demand will increase crop water requirements, which may compound the sensitivity to water stress, resulting in greater yield reductions than experienced with similar water deficits under cooler conditions.

Due to limited water resources and the unreliable annual distribution of rain, water stress also is a major constraint on potato production in South Africa (Mould & Rutherfoord, 1980). In the Northern Province, for example, which is the largest potato-producing area in the country (PPO, 1995), producers are entirely dependent on underground water resources for their irrigation needs. The continuous lowering of the water table during the early nineties has been a major source of concern to producers in that area. Water quality has also deteriorated during the last decade, making it almost unusable for potato irrigation.

In South Africa there is a growing need for water on the domestic and industrial fronts, and the agricultural sector will be obliged to use water with more care in future. At least two approaches could possibly be followed to achieve water-use savings without reducing the cultivated area. The first would be to cut down on current water use by the application of sound irrigation scheduling techniques. Surveys carried out among potato producers by the PPO have shown that irrigation management is considered an important production limiting factor. From another survey (Annandale, Van der Westhuizen & Olivier, 1996) it is, however, also evident that only a few producers do apply scheduling techniques to irrigated crops. Although yield is not determined solely by water supply, the general lack of appropriate irrigation management is emphasized by the fact that the average yield from irrigated potato crops in South Africa amounts to 28 t ha^{-1}, compared to yields of 70 t ha^{-1} and higher achieved through good management, including effective irrigation scheduling. The negative attitude of potato growers to irrigation scheduling can be attributed to various factors, but the lack of easy, quick and reliable scheduling methods seems to be an important reason why farmers do not manage irrigation effectively.

Although effective irrigation scheduling may increase water savings in the short-term, the breeding and selection of genotypes that are more efficient with regard to water-use characteristics may be a second and long-term alternative to the problem. This is a well-recognized alternative for the potato, as for many crops (Cother, Hocking & Logan, 1981; Chaudhuri, Deaton, Kanemasu, Wall, Macrarian & Dobrenz, 1986; Kvien & Branch, 1988; Pennypacker, Leath, Stout & Hill, 1990; Trebejo & Midmore, 1990; Ekanayake & Midmore, 1992). Breeding for better adaptability to drought is therefore also an objective of the local potato breeding programme at Roodeplaat.

Since little is known about the water requirements and drought tolerance characteristics of local potato germplasm, the objectives of this study were:

(1) To determine the water use of the most important potato cultivars and breeding lines to ensure maximum yield and quality.

(2) To identify critical growth stages of potatoes to water stress.

(3) To determine the effect of water stress imposed in different growth stages on growth and development.

(4) To determine the suitability of some physiological parameters to indicate the existence of plant water stress and to serve as early screening methods for drought tolerance in

potato genotypes.

(5) To use collected data to develop crop growth models and adapt irrigation scheduling models for potatoes.

In the first two data chapters of this report (Chapters 4 and 5) the effects of water stress on tuber yield, size distribution and internal tuber quality are investigated. Chapter 6 investigates the suitability of two physiological parameters, photosynthetic rate and stomatal resistance, to serve as indicators of water stress and drought tolerance in potatoes. The effect of water regimes on water use, water-use efficiencies and root distribution of different genotypes are studied in the following two chapters. In Chapter 9 the genotypes included in this study are classified according to drought tolerance. The last data chapter elaborate on the calibration and evaluation of a simulation model for the irrigation scheduling of potatoes.

The identification of critical growth stages, as well as the effects of water stress on growth and development were not attainable in this study. The main reason being the fact that plots cannot be irrigated separately when the irrigation boom is used. Therefore differential stress levels could not be applied to different plots for different growth stages. This fact was realised at the initial stages of the project and the project team was advised by the steering committee to obtain the current state of knowledge in this regard from literature. In the literature survey (Chapter 2) the effects of water stress in different growth stages of the potato crop are discussed according to reports in the literature.

CHAPTER 2

LITERATURE REVIEW

Water stress is recognized as a major constraint on potato production world-wide (Schapendonk, Spitters & Groot, 1989), with significant tuber-yield reductions being the most important outcome. It is often stated that the potato plant is very sensitive to water stress and that good yield and quality can only be achieved with a sufficient and regular supply of water (Doorenbos & Kassam, 1979; Mould & Rutherfoord, 1980; Van Loon, 1981).

The sensitivity of the crop to water stress can be attributed to many factors, one being that the onset of stress is associated with mild shortages in soil-water supply. It has been shown that the stomata of potato plants start to close at relatively high water potentials, compared to other crops (potato: -350 kPa, soybean: -1100 kPa and cotton: -1300 kPa) (Van Loon, 1981). According to Van Loon (1981), stomatal closure results in decreased transpiration and photosynthetic rates that will have a negative influence on the production of dry matter. Another factor may be the potato plant's shallow and poorly distributed root system. Doorenbos & Kassam (1979) state that potato plants extract about 70% of their water requirements from the upper 300 mm of soil and 100% from the upper 400 to 600 mm. Fulton (1970) reported that potato yield was restricted by a relatively small stress applied to only a portion of the root system, which suggests that potato roots may have a relatively low capacity for water absorption and that almost the total root system must have access to readily available water in order to produce maximum yield.

Authors' opinions differ greatly with respect to the permissible depletion of soil water before the onset of irrigation. According to Fulton (1970), potato yield is limited by soil-water potentials lower than -50 kPa in the upper 150 mm soil layer, while Mould & Rutherfoord (1980) have suggested potentials between -50 and -70 kPa in the upper 300 mm of soil. Harris (1978) and Doorenbos & Kassam (1979) recommend a 30 to 50% depletion of plant-available water from the root zone. In a previous study conducted with the cultivar Up-to-date, it was found that a 50% depletion of plant-available water from the root zone (600 mm deep) resulted in the most favourable compromise between acceptable yield, quality and water-use efficiency (Steyn, Du Plessis & Nortjé, 1992).

Water stress affects the potato plant in many ways. According to Coleman, Tai, Clayton, Howie & Pereira (1993), leaf elongation and tuber volume expansion cease when soil-water potentials are still as high as -40 to -50 kPa. Jefferies (1989) recorded a decrease in leaf growth rate when leaf water potential dropped below -280 kPa and growth ceased when it reached -1100 kPa. Water stressed crops exhibit slower and lesser canopy expansion (Jefferies, 1993; Jefferies & MacKerron, 1993) and therefore the maximum leaf area index is reduced (Van Loon 1986; MacKerron, 1989).

Water stress, furthermore, usually causes early senescence, thereby shortening the life cycle of the plants (Susnoschi & Shimshi, 1985; Van Loon, 1986). According to Spitters, Neele & Schapendonk (1988), differences in total dry matter accumulation of potato genotypes are largely explained by differences in cumulative radiation interception. It therefore seems reasonable to assume that those genotypes that maintain canopy expansion and maximum radiation interception will achieve greater dry matter production, and possibly harvestable yields, under drought conditions (Jefferies & MacKerron, 1993). The harvest index, or the fraction of assimilates partitioned to the tubers, is another important factor to be considered: Jefferies & MacKerron (1993) observed reductions in the harvest index of droughted treatments in some potato genotypes.

Since plant water status also affects physiological processes such as photosynthesis and stomatal behaviour (Van Loon, 1986), these processes have been investigated as indicators of water stress as part of this study. According to various reports, stomatal resistance is a suitable indicator of plant water status (Rutherfoord & De Jager, 1975; Dwelle, Kleinkopf & Pavek, 1981; Dwelle, 1985; Bansal & Nagarajan, 1986; Oosterhuis & Walker, 1987; Vos & Groenwold, 1989). Stomatal closure affects transpiration and photosynthetic rates, which may lead to decreased tuber yields.

The influence of water stress on the photosynthetic rates of crops, including potatoes, has been studied extensively (Munns & Pearson, 1974; Shimshi, Shalhevet & Meir, 1983; Dwelle, 1985; Van Loon, 1986; Ceulemans, Impens, Laker, Vanassche & Mottram, 1988). Reduced photosynthetic rates due to water stress have often been found (Bodlaender *et al.*, 1986; Van Loon, 1986), but marked differences in assimilation rates between genotypes (Moll, 1983) and seasons (Dwelle, Kleinkopf, Steinhorst, Pavek & Hurley, 1981) have also been reported. According to Dwelle *et al.* (1981), yield correlates poorly with photosynthetic rate and stomatal resistance, the reason being that photosynthetic rate per unit leaf area is not the sole determinant of yield. Canopy assimilation rates for the full season, as well as the partitioning of assimilates, should also be considered. According to Wilcox-Lee & Drost (1990), the partitioning of assimilates may be more important even than the actual assimilation rate in determining economic crop yields. However, since more than 90 % of the dry weight of a plant such as the potato is derived from photosynthetically fixed CO_2 (Zelitch, 1975), high photosynthetic rates are essential in order to achieve higher yields, in spite of the poor correlations sometimes recorded between short-term photosynthetic rate and yield (Dwelle, 1985). It is therefore suggested that plant breeders should strive to cross parental material with high overall photosynthetic efficiency with parents that have efficient partitioning of assimilates to the tubers.

Although single measurements of assimilation rate do not always show a correlation with tuber yield, some researchers have been able to show a correlation between the reduction in photosynthetic rate associated with water stress and drought tolerance in some genotypes. A study by Schapendonk *et al.* (1989), showed that the greatest reduction in photosynthetic rate occurred when a drought-sensitive cultivar was subjected to water stress. Sukumaran, Ezekiel & Perumal (1989), reported drought-induced reductions in assimilation rates of 32% for drought tolerant and 84% for drought susceptible genotypes.

The specific effects of water stress on yield, tuber-size distribution and tuber quality depend on the physiological stage at which the plant is exposed to the stress (Struik & Van Voorst, 1986). Water stress at almost any stage during the growing season, but especially during the tuber bulking phase (Miller & Martin, 1987b; Ojala, Stark & Kleinkopf, 1990), will result in lower tuber yield. According to Struik & Van Voorst (1986), drought reduces the number of harvestable tubers by reducing the number of tubers that grow into a certain minimum size, without affecting the number of tubers initiated. Miller & Martin (1987b) have also suggested that irrigation treatment has no effect on number of tubers and that the reduction in total yield is largely due to reduced tuber size. Haverkort, Van der Waart & Bodlaender (1990), however, have recorded a reduction in the number of stolons (and tubers) per stem as a result of early drought stress. This finding was supported by the work of MacKerron (1989), who found that the number of tubers produced per stem is influenced by the water supply in the early part of the growing season: water stress during tuber initiation phase reduces the number of potential tubers. In addition, the size distribution of tubers is usually hampered by water stress (Miller & Martin, 1987b; MacKerron & Jefferies, 1988; MacKerron, 1989). MacKerron (1989) noted that drought influences the marketable yield through two opposing effects: the reduction in total yield shifts the grade distribution downwards (a greater proportion of small tubers), while the reduction in number of tubers has a slight effect in shifting the distribution upwards.

Water stress may also have adverse effects on tuber relative density and reducing sugar content, two quality characteristics commonly affected by water supply. Tuber relative density, which gives an indication of tuber dry matter content, is usually enhanced by water stress late in the growing season (Trebejo & Midmore, 1990; Jefferies & MacKerron, 1993). Dry matter content of tubers tends to increase progressively during the growing season of the crop (Jewell & Stanley, 1989; Brown, MacKay, Bain, Grittith & Allison, 1990; Richardson, Davies & Ross, 1990b), but the pattern of increase varies greatly between crops and years (Jefferies, Heilbronn & MacKerron, 1989). The final dry matter and reducing sugar contents at harvest are influenced by cultivar, cultural practices and the environment. In some cases abnormally high sugar accumulation occurs in tubers during storage as a result of stresses to the potato plant during the last part of the growing season, such as excessively high temperatures, lack of water or high fertiliser applications late in the growing season (Sowokinos, 1990).

The dry matter content and reducing sugar content of tubers are important characteristics of tuber quality, particularly in crops intended for processing (Jefferies *et al.*, 1989). Crisping is a dehydrating process and the yield of crisps is therefore dependent on the dry matter percentage of the tubers (Logan, 1989). Tubers high in reducing sugars produce fries and crisps (dry chips) which are dark in colour due to the Maillard non-enzymatic browning reaction, involving reducing sugars and amino acids (Owings, Iritani & Nagel, 1978). Desirable colour in final products is strongly emphasized in the potato processing industry, and in the chipping industry (fries and crisps) it is absolutely critical (Orr & Janardan, 1990).

Interrupted irrigation during the growing season often leads to tuber malformations. Water stress after tuber formation can cause temporary slowing down or cessation of individual tuber growth (MacKerron, 1989). If such conditions are followed by a more favourable period, rapid renewed growth may cause tuber disorders like malformation, growth cracks and secondary growth.

CHAPTER 3

TRIAL PROCEDURES

3.1 General

The trials described in the following sections were all carried out at the ARC-Roodeplaat experimental farm north-east of Pretoria. Climatic conditions allow two growing seasons per annum for potatoes, which is typical of some subtropical climates (Levy *et al.*, 1990). In spring plantings potatoes were planted towards the end of August, when temperatures are relatively low and day lengths short. Temperatures, day length and irradiation increase as the season progresses, with maximum levels at harvesting in December. In the autumn, growth starts when temperatures are high and day length long (February), and continues under decreasing temperatures, day length and irradiation until about the end of May to early June, when plants are killed off by frost. Climatic data for the respective trial seasons are presented in Figure 3.1.

Trials started in the autumn of 1992, when the six most important potato cultivars were evaluated simultaneously. Two of the four replicates were located in each of the two rain shelters used. After the first season it was realized that the plots were too small, leading to a high level of variation in the data. It was decided to initially reduce the number of cultivars to three: the most important early- (short-) and medium-season cultivars, and a late- (long-) season cultivar which is known to be fairly drought-tolerant (Rossouw & Waghmarae, 1995). Plot size was increased from 4.5 to 5.4 m^2, resulting in a reduction in the number of replicates from four to three. There was also some concern about the small amounts of water (±7 mm) regularly received by the driest treatment, which is not typical of field situations. Two irrigation management methods, one in each of the rain shelters, were consequently evaluated during the spring planting of 1992 and autumn of 1993, using the three cultivars mentioned. The management methods are fully described in Section 3.2.

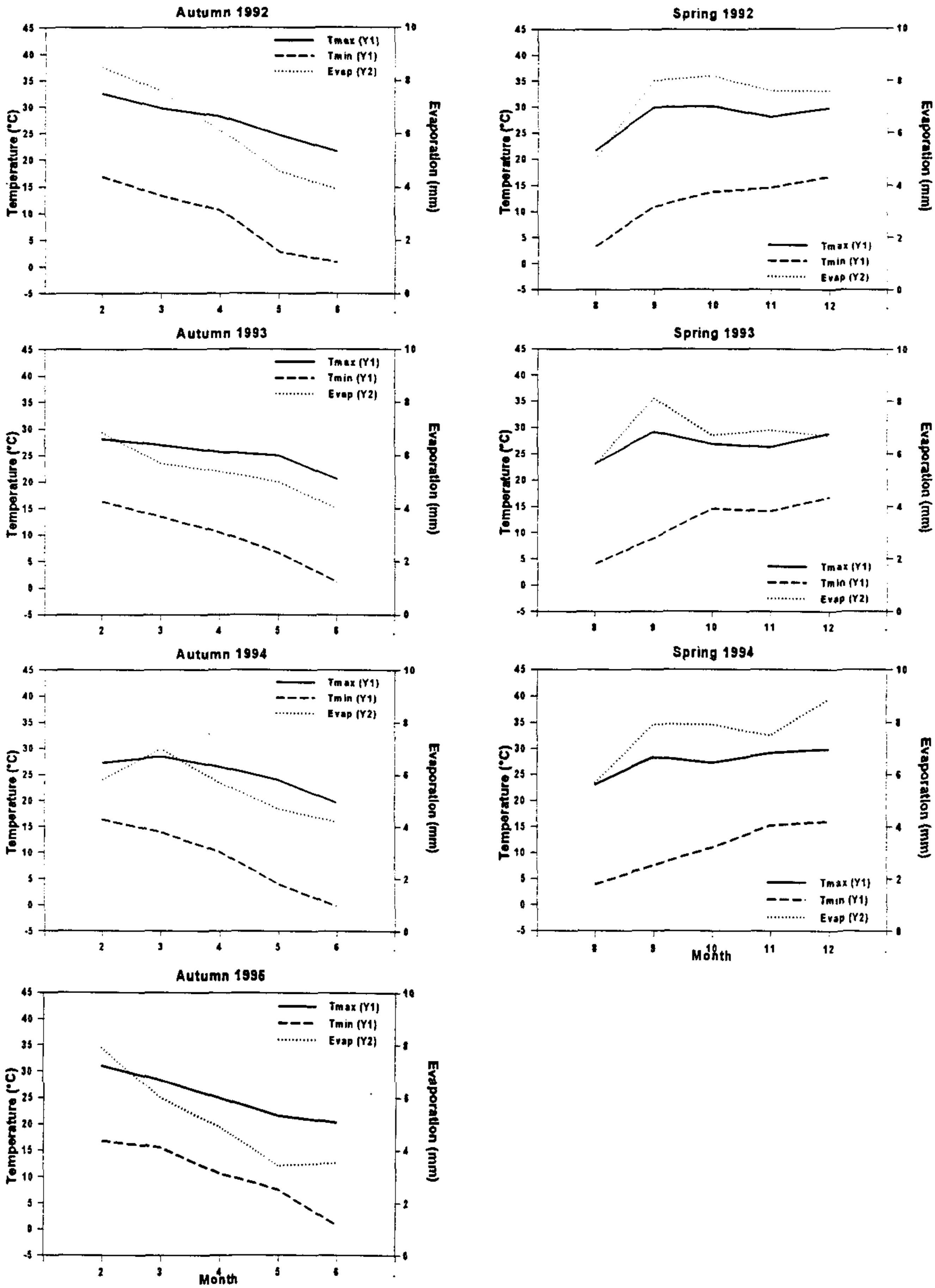


FIGURE 3.1 : Mean daily minimum and maximum temperatures, as well as average daily Class A-pan evaporation for the months of the different seasons during the trial period

In the first three plantings described above, cultivars ranging from very short to very long growing seasons (early to late cultivars) were included in the same trial. Consequently, by the time that some cultivars had senesced, others were still actively growing. This posed problems with the method of irrigation used, where cultivars could not be irrigated separately. It was therefore decided to group cultivars in more or less the same maturity class in subsequent trials. Late- to medium-late cultivars were grouped in one rain shelter, while medium to early cultivars were grouped in the second shelter. In all subsequent plantings, Late Harvest was included as a standard late cultivar and Up-to-date as a standard medium cultivar. Two other genotypes (cultivars or breeding lines) of the same maturity class were included with each of the standards. Each of the genotypes was evaluated in both a spring and an autumn planting, starting in the spring of 1993 until the autumn of 1995. Details of the genotypes included in the various trials are presented in Table 4.1.

3.2 Field screening technique for water use and drought tolerance studies

Introduction

The well-documented sensitivity of potatoes to drought (Van Loon, 1981) is a major concern in South Africa due to its low annual rainfall and poor rainfall distribution in most parts of the country (Mould & Rutherfoord, 1980). Consequently, a major objective in potato plant breeding programmes for rainfed conditions in semi-arid regions, such as South Africa, is the selection of more drought-tolerant material (Mahalakshmi, Bidinger & Rao, 1990). In the local breeding programme, selection for better adaptability to drought is aimed not only at dry-land potato production, but also at production under irrigation, as water is a limited resource also for irrigation farmers.

Evaluating the relative performance of cultivars in locations where drought is likely to occur is dependent on annual weather changes and is extremely time consuming (Mahalakshmi *et al.*, 1990). Methods have consequently been developed to induce drought stress in the more controlled environment of a glasshouse (Pennypacker *et al.*, 1990), including methods that rely on regulating the timing and amount of water given to the potted plant (Rossouw & Waghmarae, 1995) and the incorporation of an osmoticum such as polyethylene glycol (PEG) into the growth medium (Schapendonk *et al.*, 1989). Although these methods induce stress, there are potential problems with most of them. The use of osmotica like PEG and NaCl lower the soil-water potential, but may have additional adverse effects on the plant. PEG may interfere with phosphate uptake and be toxic to plants (Emmert, 1974 referred by Pennypacker *et al.,* 1990), while NaCl may cause salinity stress to the plants. The effect of drought may thus be confounded by other stresses in the plant. In pot trials, water stress usually develops rapidly due to container size. This is in contrast to the gradual development of drought in the field, which allows plants to acclimatise to the stress (Pennypacker *et al.,* 1990). Biotechnological screening methods include the search for drought-related proteins (Van der Mescht, De Ronde & Rossouw, 1992), but even these methods need to be verified by the evaluation of field performance (Rossouw & Waghmarae, 1995). From the preceding discussion, there is clearly no reliable alternative to field screening for drought tolerance in plants at this stage.

The line-source sprinkler irrigation technique (Hanks, Keller, Rasmussen & Wilson, 1976) has recently been used extensively in water-use and drought-screening trials (Bresler, Dagan & Hanks, 1982; Barragan & Recasens, 1988; Mahalakshmi *et al.*, 1990; Fernandez, 1991; Singh, Rao & Williams, 1991). The system gives rise to a continuously variable soil-water regime along a gradient from excess water to no water added. It also has the advantage of minimizing the experimental area, since there is no need for border rows because of the small incremental change in water applied between adjacent treatments (Mahalakshmi *et al.*, 1990). The experimental design is similar to a strip-plot or strip-block design, except that irrigation levels are systematically arranged without randomization (Fernandez, 1991). Other factors, such as genotypes or fertility levels, can be studied by placing treatment variables in strips at right angles to the irrigation treatment (Hanks, Sisson, Hurst & Hubbard, 1980). Since water treatments are not randomized there is no valid univariate statistical test available to test for the main effects of water (Fernandez, 1991, Hanks *et al.*, 1980). The irrigation effects are, however, usually large and, according to Hanks *et al.* (1980), there should be no need to assign a probability level to their significance. Some statistical techniques have since been developed to overcome the problem (Bresler *et al.*, 1982; Fernandez, 1991) and the line-source technique is widely used today in irrigation trials for many crops.

In areas where the rainy season coincides with the growing season of the crop, rains often interfere with water-stress treatments in the field (Fletcher & Maurer, 1966). Automated rain shelters have consequently been used to eliminate the interference of rain with water treatments (Upchurch, Ritchie & Foale, 1983; Kvien & Branch, 1988; Jefferies, 1993). Rain shelters usually have moveable roof structures on elevated rails or are building-like structures that move on surface-level rails (Kvien & Branch, 1988). Due to the limited space covered by rain shelters, as well as the fact that the rain shelters used in the present study moved on elevated rails, the conventional line-source system could not be used. The use of rain shelters was therefore combined with a modified version of the line-source irrigation system to evaluate water use and drought tolerance of potato genotypes.

Rain shelters and Irrigation systems

The trials were conducted at Roodeplaat near Pretoria during the period 1992 to 1995. Each of the two rain shelters covered an area of 280 m^2 (24 x 11.7 m). The roof structure of the shelters consisted of a steel construction, similar to that used for commercially available greenhouses. Polyethylene sheeting was used to cover the roof and sides of the shelters. The shelters were fully automated and driven by 380 V three-phase motors. A drop of rain onto a small sensor activated the motors to cover the trial. Once the sensor was dry (after a shower), the shelter automatically moved to the open position. This restricted the time the plants were covered. Limit switches on either end of the rails prevented the shelter from running off the rails. A complete description of the construction and operation of the shelters is given by Nortjé (1988).

The line-source principle (Hanks *et al.*, 1976) was used as a departure point and adapted for use with rain shelters to allow the inclusion of water levels and cultivars as treatments. A travelling boom, mounted on an A-frame was attached to the inside roof structure of each shelter. The A-frame had four wheels that moved in tracks along the length of the shelter and was driven by a 220V electric motor. Limit switches on both sides of the shelter ensured the continuous shuttling of the boom along the shelter, as long as the power was switched on. Water was supplied to the boom by means of a trailing hose that moved along with the boom. The same applied to the electricity supply to the electric drive motor. Flat fan nozzles were mounted onto the boom (constructed of 25mm galvanised pipe) at a spacing of 750 mm. This spacing allowed the spread of 15 nozzles across the width of the boom. Five water-treatment strips of three rows each were achieved by the use of Tee-jet (R) nozzles with different discharge rates. This resulted in a step-wise change in the amount of irrigation, instead of the gradual decline associated with the conventional line-source. The nozzles had a 50 ° spray angle to prevent overlapping with adjacent rows and plots. PVC plastic sheeting (0.4 mm in thickness) was installed to a soil depth of 1 m between water-treatment strips to prevent lateral water movement. It is assumed that the adjacent water treatments had no effect on each other.

Whenever irrigation was necessary, the shelter was drawn over the crop, the water hose and power supply connected and switched on. Canvas strips attached to the side panels of the shelter were let down before irrigation to limit water drift caused by wind. Irrigation water was supplied from a 10 000-litre reservoir with the aid of a booster pump. A constant operating pressure of 120 kPa was ensured by the use of pressure regulators. At constant pressure the fraction of the total amount of water which was applied by a nozzle of specific size remained the same. It was therefore possible to calculate the exact amount of water applied to each treatment, as the discharge rate of each nozzle at 120 kPa was known.

The accuracy of water application could not be checked by catch cans or rain gauges as is usually done (Miller & Martin, 1987b; Trebejo & Midmore, 1990), because of the uneven distribution of water within the same treatment. The Tee-jet nozzles used are designed to overlap 30% in their spray pattern in order to ensure even water application. At the spacing of 750 mm and 50° spray angle, the rate of application was therefore uneven, leading to dry (between the rows) and wet strips (on the rows) (Figure 3.2). The boom was therefore occasionally checked during each season by collecting the discharge of each nozzle in plastic containers during a twenty-second period. This was done while the boom stood stationary in the open position. The results of some checks are shown in Table 3.1 as an example.

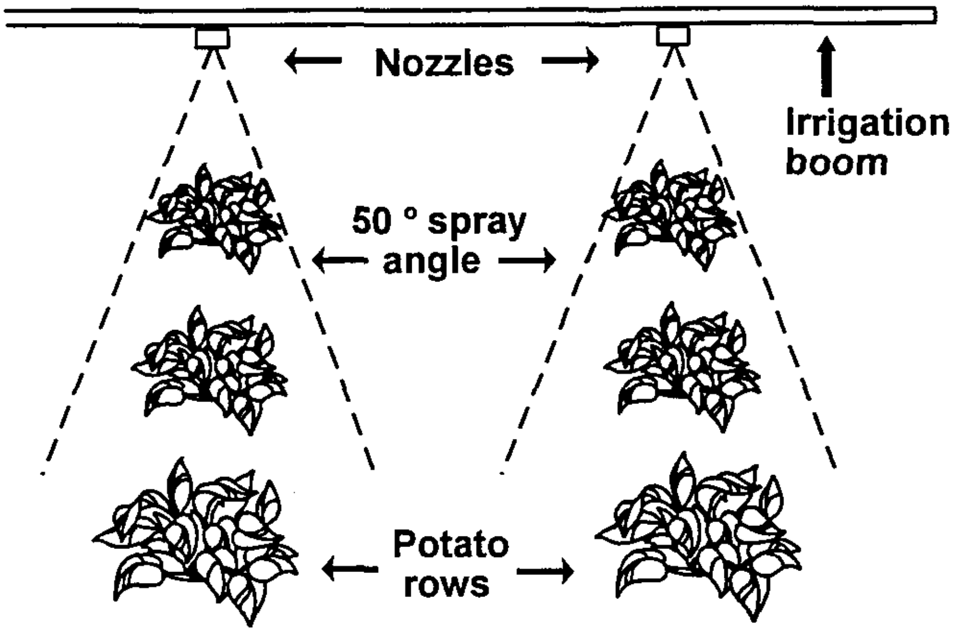


FIGURE 3.2: **Schematical presentation of the spray pattern of irrigation nozzles to prevent overlapping with adjacent plots**

The amount of water discharged by the nozzles of each treatment is expressed as a fraction of the amount applied to the wettest treatment (W1). The total amount of water applied to each treatment is therefore easily calculated.

The irrigation scheduling of the W1 treatment was based on neutron-probe measurements of the soil-water content. A maximum depletion of 20 % of the water held at field capacity (in the zone of active roots at that stage) was allowed for this treatment. At full canopy, irrigation scheduling was based on a rooting depth of 600 mm. For the specific soil it resulted in W1 being irrigated whenever about 25 mm of soil water was depleted. For the 1993 planting, for example, treatments W2, W3, W4 and W5 of rain shelter # 1 received 20.5 mm, 16.25 mm, 11.5 mm and 7.5 mm, respectively, every time W1 was irrigated 25mm (Table 3.1). In the 1992 spring and 1993 autumn plantings two irrigation management methods, one in each of the rain shelters, were evaluated. The irrigation scheduling of rain shelter # 1 was carried out

Table 3.1 : Discharge rates of different nozzles used in five water treatments. Amounts in mℓ water collected per 20-second period. Standard error of means in parenthesis

Date mm-yy	Rain shelter no.	Water treatment									Total mℓ
		W1	W2		W3		W4		W5		
		mℓ	mℓ	%	mℓ	%	mℓ	%	mℓ	%	
10-93	1	775 (4.9)	633 (7.1)	81.7	428 (3.5)	55.2	347 (3.8)	44.7	215 (1.1)	27.8	2398
11-94	1	666 (6.9)	586 (5.6)	88.5	411 (2.6)	61.7	334 (3.6)	50.1	210 (4.8)	31.5	2207
04-95	1	743 (2.4)	616 (2.6)	83.0	417 (1.5)	56.1	341 (1.8)	46.0	210 (1.3)	28.3	2327
10-93	2	751 (6.02)	626 (5.2)	83.2	432 (3.6)	57.5	351 (0.7)	46.7	212 (1.8)	28.2	2371
11-94	2	729 (9.2)	604 (6.5)	82.9	427 (6.3)	58.6	341 (3.8)	46.8	201 (5.2)	27.6	2302
4-95	2	739 (2.0)	607 (1.4)	82.2	416 (1.7)	56.3	340 (1.1)	46.0	210 (2.2)	28.4	2312

according to the method described above. In rain shelter # 2, the drier treatments were, however, not irrigated simultaneously with W1. The fractions of water they were suppose to receive were accumulated, so that all treatments were irrigated a minimum of 20mm per application. The purpose of the investigation was to determine whether genotype performance is influenced by the irrigation amount per application, as there was some concern about the small amounts of water (±7mm) regularly applied to the driest treatment (W5) of rain shelter # 1.

The bronze nozzles were replaced annually as it was observed that wear and tear started to change the discharge rates after some time. Special attention was paid to ensure that irrigation water was sufficiently filtered and free of materials that could cause nozzle clogging. Nozzles were also removed and cleaned regularly to prevent furring of the orifices. Actual water use and yield data obtained from trials conducted according to the described technique are presented in Chapters 4 and 7.

CHAPTER 4

THE EFFECTS OF DIFFERENT WATER REGIMES ON TUBER YIELD AND SIZE DISTRIBUTION

4.1 Introduction

The detrimental effects of drought on potato tuber yield are well known (Struik & Van Voorst, 1986; Miller & Martin, 1987b; Levy *et al.*, 1990; Spitters & Schapendonk, 1990). In general, total tuber yield is reduced by water stress at almost any stage during the growing season of a potato crop (Mould & Rutherfoord, 1980), but especially during the tuber bulking phase (Miller & Martin, 1987b; Ojala, Stark & Kleinkopf, 1990).

Apart from lower total tuber yield, water stress may also adversely affect the tuber-size distribution (Struik & Van Voorst, 1986; Miller & Martin, 1990). Miller & Martin (1987b) have suggested that the reduction in total yield as a result of water stress is largely due to reduced tuber size. Droughts generally cause a downward shift in tuber-size distribution. According to Struik & Van Voorst (1986), drought reduces the number of harvestable tubers by reducing the number of tubers that grow beyond a certain minimum size. The consequence of drought is, therefore, that a smaller fraction of the total yield reaches the minimum size required for a specific size class (MacKerron & Jefferies, 1988). This may not be desirable as most markets have specific preferences regarding the optimum tuber size required.

Little is known about the response of South African potato cultivars to water stress. From an earlier study conducted with the cultivar BP1, Mould & Rutherfoord (1980) concluded that physiological disorders and poor processing quality result from early water stress, while tuber yield is severely hampered by stress during the latter half of the bulking period. Jefferies & MacKerron (1987) reported differences between cultivars in reductions of yield because of drought. They also showed that drought affects the size distribution of cultivars differently.

Changes in tuber-size distribution may have significant consequences for the producer, as his product may not satisfy the needs of the consumer, be it for processing or the fresh market. In this chapter the result of different water regimes on total yield and tuber-size distribution of some commercial potato cultivars and breeding lines is investigated.

4.2 Materials and methods

Field experiments were conducted on a sandy loam (Oakleaf soil form) at the ARC-Roodeplaat Vegetable and Ornamental Plant Institute near Pretoria during the period 1992 to 1995. The soil has an average clay content of 15% in the upper 600 mm of the profile, is well drained and has a volumetric field capacity of about 25%.

The genotypes evaluated during the different plantings are listed in Table 4.1. Seven trials were carried out during the test period. An irrigation boom (Chapter 3, section 3.2) was used to impose five different water treatments. The control treatment (W1) was irrigated when 20% of the water held in the soil at field capacity was withdrawn from the root zone. The other treatments (W1 - W5) were irrigated simultaneously, and received approximately 82%, 62%, 46% and 30% respectively of the amount applied to W1 (see Table 3.1 for specific fractions applicable to the different plantings). Soil-water content was determined three times per week to a depth of 1200 mm by neutron probe (CPN 503). Automatic rain shelters prevented the interference of rain with irrigation treatments. Details of the trial layout, as well as the experimental design, are presented in Chapter 3, sections 3.1 and 3.2.

The same rain shelter site was used during the entire trial period, but the area planted alternated between the two positions covered by each rain shelter. The part that was planted during the spring planting was the stationary position of the rain shelter in the autumn, and *vice versa*. The soil was fumigated with methyl bromide at a rate of 60 g m^{-2} before each planting to limit the possible adverse effects of successive potato crops. A rototiller was used for seedbed preparation, whereafter furrows were made using a two-wheel tractor and potato

TABLE 4.1 List of genotypes included in water use trials conducted in spring and autumn plantings over four years.

Year	Planting	Rain shelter #1		Rain shelter #2	
		Genotype name	Maturity class	Genotype name	Maturity class
1992	Autumn	Vanderplank	Early	Vanderplank	Early
		Buffelspoort	Early	Buffelspoort	Early
		Up-to-date	Medium	Up-to-date	Medium
		BP1	Medium	BP1	Medium
		Kimberley Choice	Late	Kimberley Choice	Late
		Late Harvest	Late	Late Harvest	Late
1992	Spring	Vanderplank	Early	Vanderplank	Early
and		Up-to-date	Medium	Up-to-date	Medium
1993	Autumn	Late Harvest	Late	Late Harvest	Late
1993	Spring	Late Harvest	Late	Up-to-date	Medium
and		Hoëvelder	Late	82-252-5	Medium
1994	Autumn	Mnandi	Medium-late	83-252-1	Medium-early
1994	Spring	Late Harvest	Late	Up-to-date	Medium
and		81-163-40	Medium-late	Mondial	Medium
1995	Autumn	83-363-67	Medium-late	84-304-4	Medium

ridger. Fertiliser and insecticide (aldicarb) were banded in the furrows at recommended rates An example of a typical fertiliser application is shown in Table B12 of the Appendix.

The potato seed pieces were planted by hand at a row spacing of 750 mm and 300 mm within the row. Weeds were controlled manually by hoeing. The potatoes were ridged (hilled) 3 to 4 weeks after emergence, when plants were about 300 mm in height. Run-off was prevented during the season by small dams across the furrows at either edge of each plot. All plots were initially irrigated uniformly, using another set of nozzles, to ensure good emergence and establishment of the crop. Irrigation treatments were initiated 3 to 4 weeks after emergence and continued until the date of senescence or haulm destruction, whereafter the dry treatments were irrigated 10 - 15 mm to ease the harvesting process.

Tubers were lifted by hand two weeks after haulm killing to ensure proper skin set, graded into different sizes and weighed. Grading of tubers was done according to the categories that were the commercial standards at the start of the trial, namely:

1. "Chats" (not marketable)	<50 g
2. Small	50 - 100 g
3. Medium	100 - 250 g
4. Large	>250 g

The marketable yield used in the analysis of data consisted of the small, medium and large tubers. The yield of chats was generally very low and excluded from the data. Tuber quality aspects such as secondary growth, mechanical damage and tuber diseases were not taken into consideration in the total yield calculations. Generally almost no diseases or mechanical damage occurred for any of the trials. Secondary growth was, however, common for some genotypes in the hot spring plantings. These deviations were more pronounced for the heat sensitive genotypes, such as Up-to-date.

The format of the trial was changed after the first autumn planting (see Section 3.1 for details). The first autumn trial was considered a pilot trial and its results were analysed separately, using the AMMI (additive main effects and multiplicative interaction) model as described by Yau (1995). For the remaining years the marketable yields for the same plantings (either spring or autumn) were combined and the AMMI model was used for data analysis. The model is able to combine and analyse data from trials in different environments, even if all the entries (genotypes) are not present in all trials. This is a suitable method to compare environment X genotype effects over seasons (Yau, 1995). The 1992 spring and 1993 autumn trials in rain shelter #2 had a different irrigation management method (Chapter 3). The data were, however, not excluded from the data set, as the relative performance of the cultivars involved did not seem to change as a consequence of management method. The data of the spring and autumn plantings were analysed separately due to expected different reactions to water treatments in the two plantings. This trend was reported by Lemaga & Caesar (1990), who worked in similar conditions in a subtropical climate. Such differences in yield can be attributed to the differences in temperature, day length and irradiation levels between spring and autumn plantings (see Section 3.1). The same standard cultivars were not used in the two rain shelters because of differences in maturity classes, and could therefore not be compared directly. In the two plantings mentioned above, there were different maturity classes in the same rain shelter, but for the purpose of data analysis, the genotypes in rain shelter #1 were considered late cultivars, and those in rain shelter #2 medium cultivars.

4.3 Results and discussion

4.3.1 Tuber yield

AUTUMN 1992 (PILOT TRIAL)

Since the relationship between water applied and water used was linear, the fractions of water applied to the different water regimes are plotted in the water-yield curves. Figure 4.1 display the absence of genotype X water interaction for this trial (summary of the AMMI analysis of variance in Table B1 of the Appendix for a). The genotypes all follow the same declining trend in yield with less water used.

The mean yield of each genotype (over water treatments) was plotted against their corresponding "interaction of principal components analysis" (IPCA1) scores (Figure 4.2). The magnitude of the IPCA1 scores indicate the degree of interaction between genotypes and different levels of water. A large positive or negative score is an indication that the genotype shows strong interaction with different levels of water. A genotype might, for instance, perform well at a sufficient level of water, but be poorly adapted to lower levels of water, and *vice versa.* A small score, on the other hand, indicates that the genotype has a more stable response to a range of water levels. Genotypes with similar response to water are grouped together according to a hierarchical clustering of AMMI estimates over water levels. The average yields for water treatments (over genotypes) were also plotted against their corresponding IPCA1 scores on the same biplot. Grouping of genotypes and water treatments on the same side of the zero score line indicates that those genotypes will respond well to that

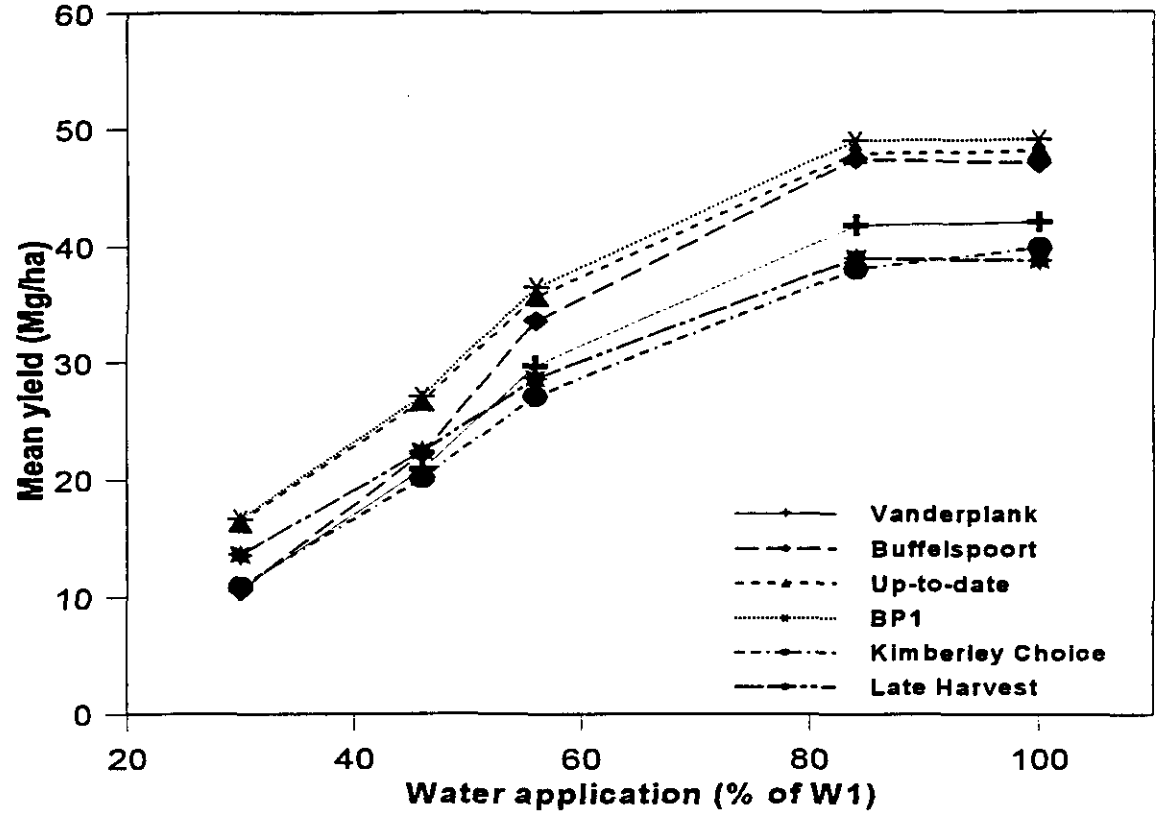


FIGURE 4.1 : Water-yield curves of six potato genotypes exposed to five levels of water during the autumn 1992 season (pilot trial)

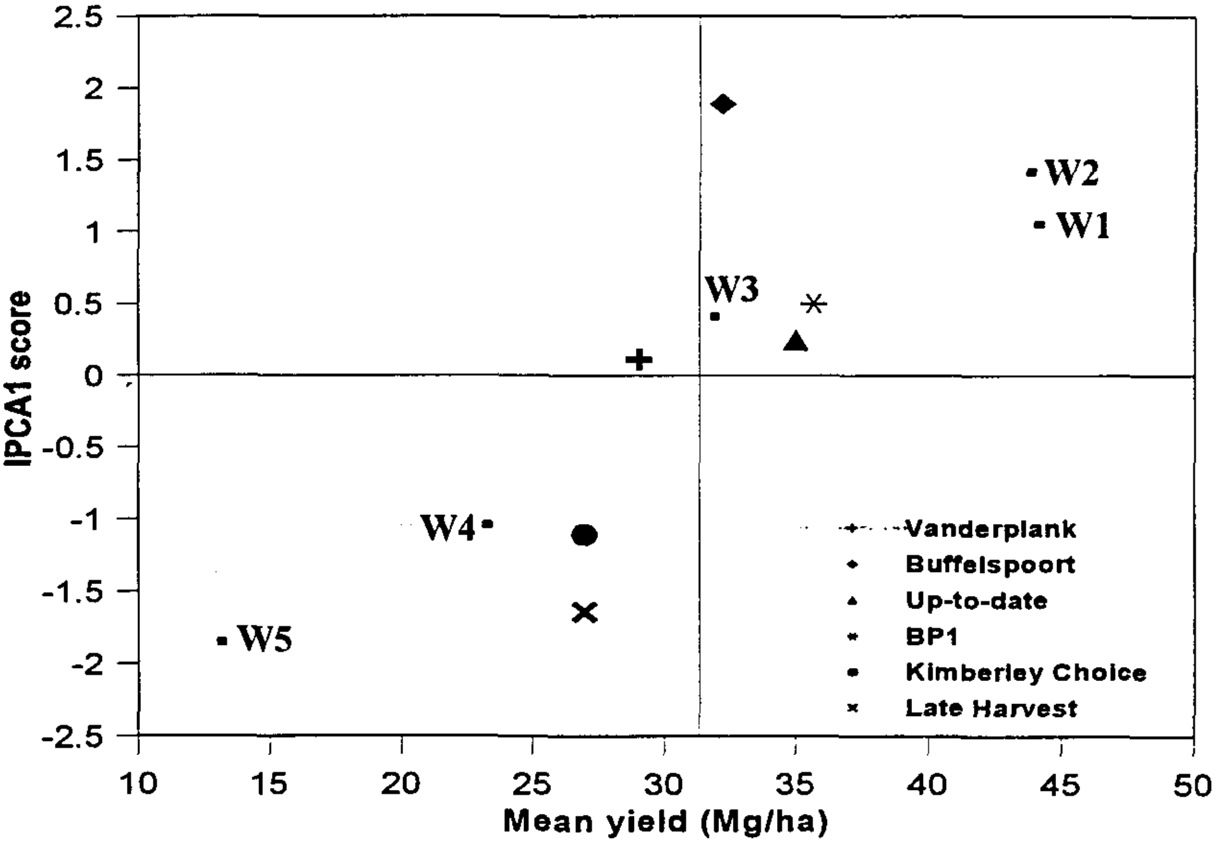


FIGURE 4.2 : AMMI IPCA1 scores and mean tuber yield of six potato genotypes as influenced by five levels of water during the autumn 1992 season (pilot trial)

water treatment. The further the points are apart, the greater the contrast between the response of a specific genotype and water treatment. It is therefore possible to get a quick visual impression of the expected performance of genotypes at certain levels of water.

Water levels W1 and W2 grouped together and contrasted with the other water treatments, indicating that the responses to both were very similar (Figure 4.2). The genotypes Buffelspoort, Kimberley Choice and Late Harvest showed the greatest interaction with levels of water. The Buffelspoort score contrasted strongly with the dry treatment scores, indicating that Buffelspoort performs best at the wetter treatments. The scores of the two late cultivars, Late Harvest and Kimberley Choice, on the other hand, contrasted with the wet treatment scores, indicating that they performed worse than the other genotypes with ample supply of water. Genotypic differences in average yield were small and all the genotypes grouped around the average yield of 32.3 Mg ha^{-1}. Late Harvest and Kimberley Choice, the two longer growers, had the lowest average yields, while the medium cultivars Up-to-date and BP1 had the highest yields.

SPRING 1992 TO AUTUMN 1995 PLANTINGS

Some variation in the marketable yield of the standard cultivars (Late Harvest and Up-to-date) was observed over years, especially in the autumn plantings (see Tables B2 and B3 of the Appendix and the graphical presentation of actual yield and yield components in Figures 4.11 to 4.14, section 4.3.2). It was therefore clear that the physical yields of genotypes in different years could not be compared. To enable comparison of genotypes over years, the marketable yield of genotypes was expressed relative to that of the standard cultivar in the same trial. In the case of the medium-late and late genotypes, yield was expressed relative to that of Late Harvest, while Up-to-date was the standard for comparison of the medium and early genotypes.

The correctness of certain assumptions were necessary to ensure valid comparisons of the relative yield of genotypes over years. It was firstly assumed that the yield of the standard cultivars was typical ("normal") in all the trials. Secondly, it was assumed that the physiological age of seed tubers, which may have a considerable effect on the performance of progeny plants (Caldiz, 1991; Pieterse, 1994), was optimal in all trials. Care was taken to ensure that all seed tubers were at optimal physiological age when planted. Problems were, however, encountered in one planting, as discussed in Section 4.3.2. A further assumption was that the yield of the genotypes would remain the same relative to that of the standards over all the years for the same planting (spring or autumn); external factors that might have differential effects on different genotypes were thus assumed to be absent. If they were present, the ranking of cultivars might have changed as a consequence.

No abnormalities in growth were observed, except for one case in the 1994 spring planting, when the genotype 84-304-4 died off early because of *Erwinia* spp. infection. Yields of the standards also remained relatively stable for the same planting (spring or autumn) (Figures 4.11 to 4.14), except for the autumn 1995 planting, when the yields were generally low (presumably due to lower levels of solar radiation), suggesting that their growth could be assumed to have been optimal in all the trials.

Late genotypes The mean relative yields of genotypes (over water treatments) were plotted against their corresponding IPCA1 scores. This was done separately for the spring and autumn plantings (Figures 4.3 and 4.5). For all the trials since the 1992 spring planting the magnitude of the IPCA1 score indicates the interaction of a genotype with water regimes, relative to that of the standard cultivar. A high score indicates that the genotype reacted differently to the irrigation treatments, compared to the standard cultivar. Summaries of the AMMI ANOVA's are presented in Tables B4 and B5 of the Appendix.

In the spring plantings, Hoëvelder and 83-363-67 were the most stable genotypes, and both had higher average yields than Late Harvest (Figure 4.3). They performed best at the wet to intermediate water treatments (W1 to W3). Mnandi had the highest overall yield, but the biggest interaction with water levels. The average yields of Vanderplank, Up-to-date and 81-163-40 were almost the same, and all lower than that of Late Harvest. They all showed strong interaction with water.

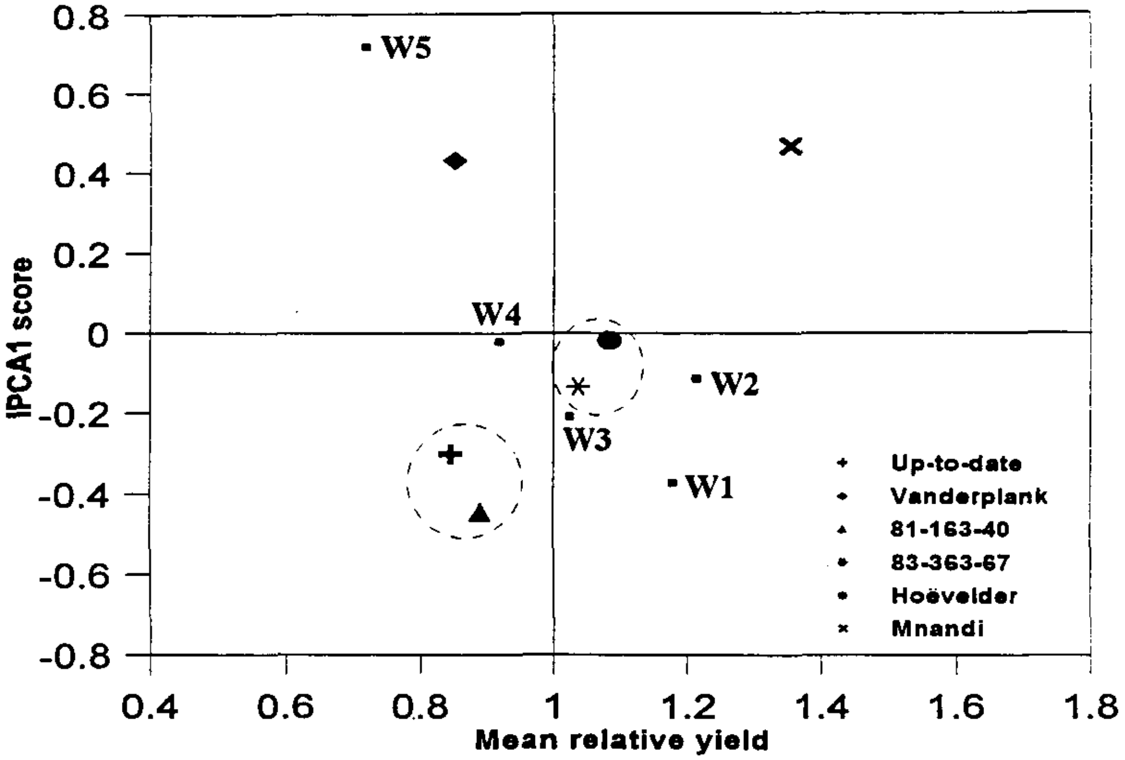


FIGURE 4.3 : AMMI IPCA1 scores and average relative tuber yields (relative to Late Harvest) of six late potato genotypes as influenced by five levels of water during the 1992 to 1994 spring seasons

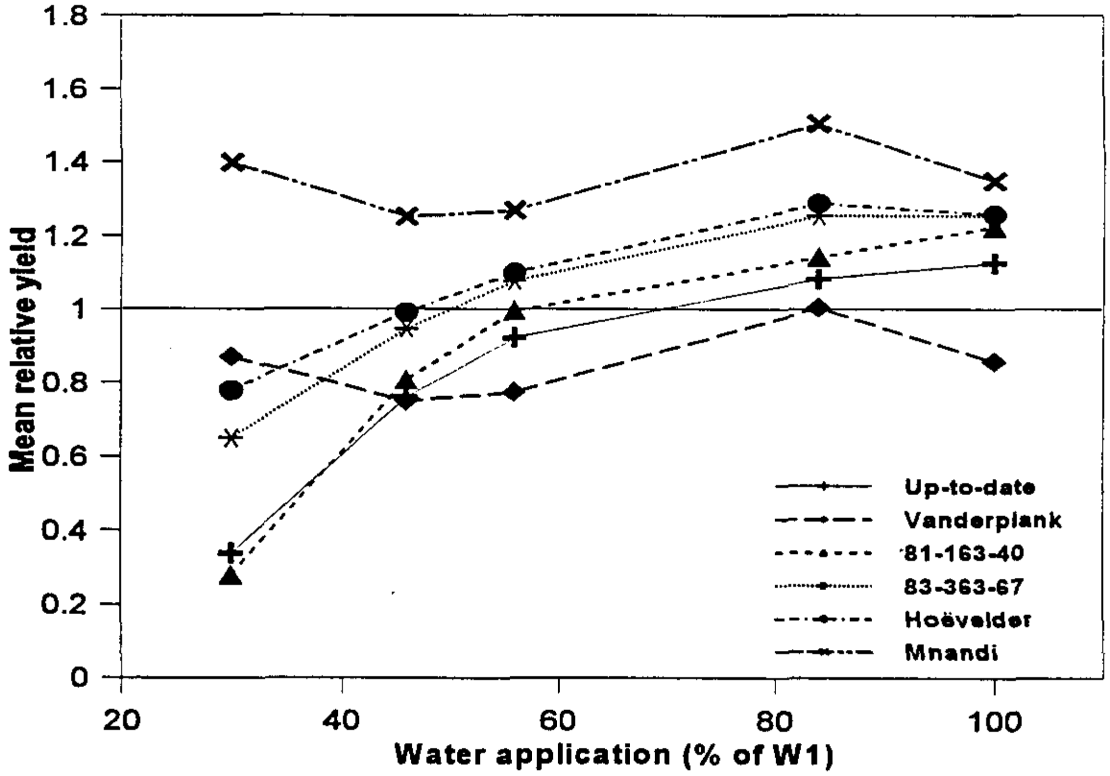


FIGURE 4.4 : Relative water-yield curves (to Late Harvest) of six late potato genotypes exposed to five levels of water stress during the 1992 to 1994 spring seasons

TABLE 4.2: AMMI preferential ranking of genotypes compared with Late Harvest as a standard according to their marketable yields at different water treatments in spring plantings

Rank no.	Water treatment				
	W1	W2	W3	W4	W5
1	Mnandi	Mnandi	Mnandi	Mnandi	Mnandi
2	Hoëvelder	Hoëvelder	Hoëvelder	Late Harvest	Late Harvest
3	83-363-67	83-363-67	83-363-67	Hoëvelder	Vanderplank
4	81-163-40	81-163-40	Late Harvest	83-363-67	Hoëvelder
5	Up-to-date	Up-to-date	81-163-40	81-163-40	83-363-67
6	Late Harvest	Vanderplank	Up-to-date	Up-to-date	Up-to-date
7	Vanderplank	Late Harvest	Vanderplank	Vanderplank	81-163-40

The AMMI preferential ranking of genotypes according to their performance at the different water levels is shown in Table 4.2. It is clear that there is almost no change in ranking between water levels W1 and W2, the reason probably being that for the W2 treatment, the soil profile could supply the portion of water usage not supplied by irrigation. When water is reduced to the level of W3, but especially at W4 and W5, the ranking of Late Harvest and Vanderplank improved from the last two positions to the second and third position, respectively. Due to its high yield potential, Mnandi remained in the first position throughout water treatments, in spite of its high interaction with water. Up-to-date, 81-163-40 and 83-363-67 moved down to the last three positions at the driest treatment (W5).

These rankings can also be represented graphically to illustrate the change in relative yields over water treatments (Figure 4.4). This may be seen as the "relative production function" of genotypes over water treatments. The response of genotypes which have relative production curves parallel to those of the standard, is similar to that of the standard. According to Figure 4.4, the response of both Mnandi and Vanderplank is similar to the response of Late Harvest, with the yield of Mnandi consistently higher and Vanderplank consistently lower than that of Late Harvest. The level of water does therefore not influence the selection of these two genotypes.

The other genotypes (Up-to-date, 81-163-40, 83-363-67 and Hoëvelder) showed a decline in relative yield with lower water use. They yielded better than Late Harvest at the wet treatments, but performed worse than Late Harvest when stressed. Of the latter four genotypes, Hoëvelder consistently had the highest yield and Up-to-date and 81-163-40 the lowest. The selection of these genotypes by the producer is therefore largely influenced by availability of water in spring plantings. When supply of water is ample, all genotypes except Vanderplank will produce higher yields than Late Harvest. When severely stressed, only Mnandi produces higher yields than Late Harvest. Vanderplank consistently had lower yields than Late Harvest, but remained stable, relative to Late Harvest. The lower yield of Vanderplank is partly attributable to it being an early cultivar, commonly associated with a lower yield potential (Levy *et al.*, 1990).

In autumn the main effects (genotypes and water levels) were significant, but the interaction between genotype and water level was not. Genotypes reacted similarly to levels of water and average yield declined with less water used (Figure 4.12). The close grouping of the mean relative yields at the different water treatments (W1 - W5 on the AMMI biplot) around the Late Harvest mean (relative yield of one) is striking (Figure 4.5). This indicates that at any of the water treatments the mean yields of the other genotypes did not change relative to that of Late Harvest, and were almost the same. The mean yield (over water treatments) was highest for 81-163-40, followed by Mnandi. Hoëvelder was the only genotype that showed considerable interaction with levels of water. The average yields of Hoëvelder, Up-to-date and 83-363-67 were lower, but close to those of Late Harvest, while Vanderplank had markedly lower yields on average. The stable relative yields of genotypes over water treatments were confirmed by their relative production functions (Figure 4.6), which followed the same tendency as Late Harvest.

Medium to early genotypes In the spring plantings only the main effect of water was significant, although genotypes showed different responses to water (Figure 4.8). Although trends were evident, the high coefficient of variance (CV = 35%) probably accounted for the interaction not being significant (summary of ANOVA presented in Table B6 of the Appendix).

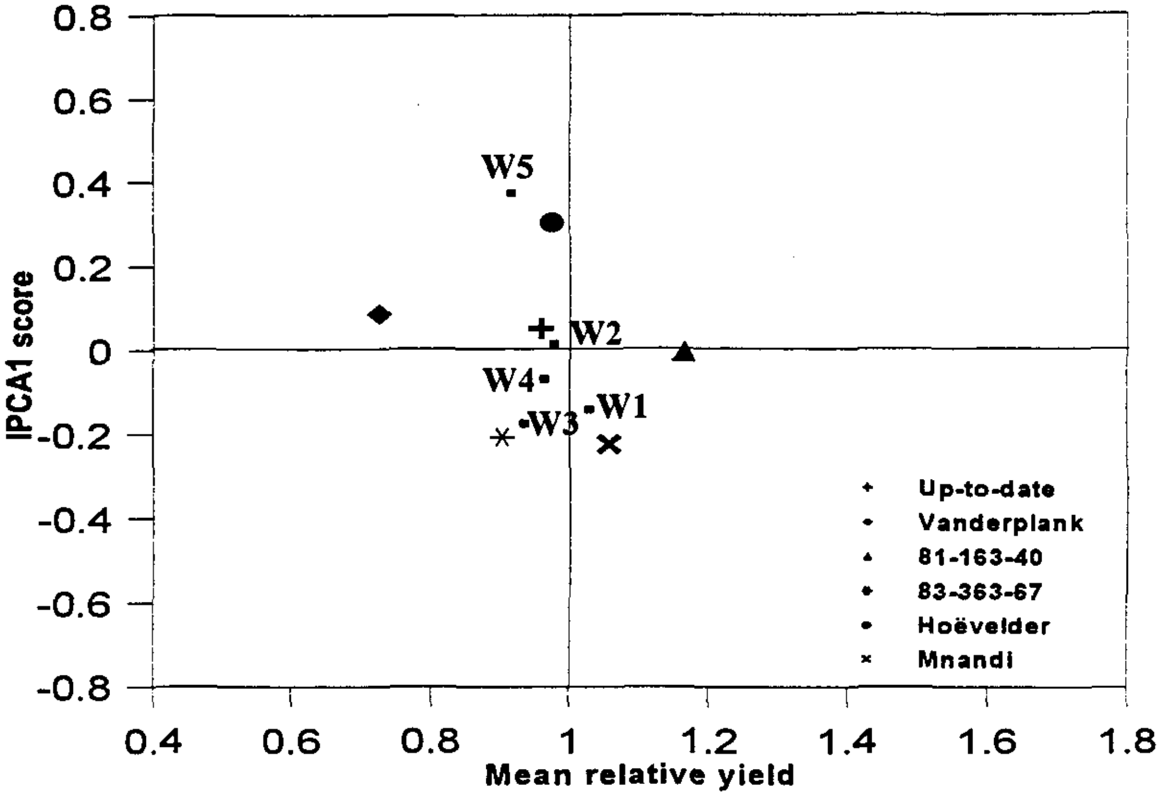


FIGURE 4.5 : AMMI IPCA1 scores and average relative tuber yields (relative to Late Harvest) of six late potato genotypes as influenced by five levels of water during the 1993 to 1995 autumn seasons

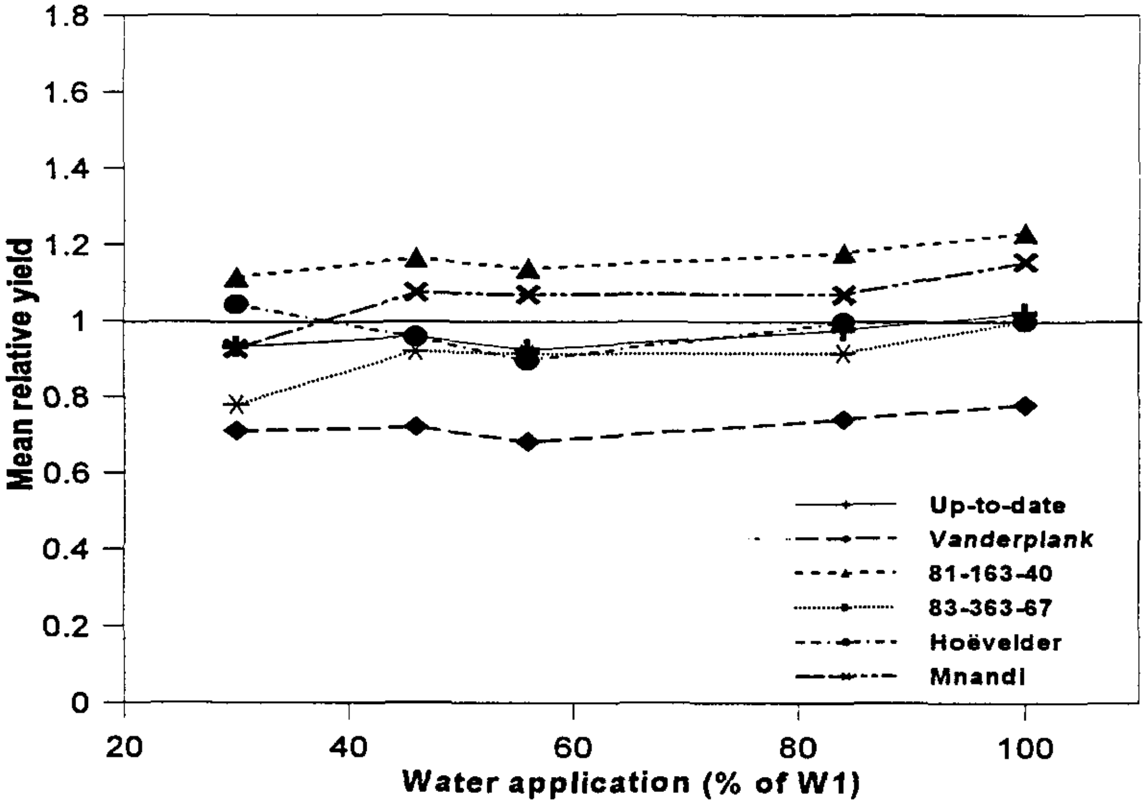


FIGURE 4.6 : Relative (relative to Late Harvest) water-yield curves of six late potato genotypes exposed to five levels of water stress during the 1993 to 1995 autumn seasons

The relative yield at W4 and W5 contrasted strongly with the yields at the wetter treatments (W1 to W3), which grouped closely together (Figure 4.7). For the wetter treatments (W1-W3) the mean yields of the other genotypes were on average lower than those of Up-to-date (< 1), while their yields were higher than those of Up-to-date at the drier treatments (W4 and W5). At W5 the yields of the other genotypes were on average almost 1.8 times those of Up-to-date. Although not statistically significant, the performance of 82-252-5 and 83-252-1 improved substantially, relative to Up-to-date, in the drier treatments (Figure 4.8). The genotypes 82-252-5 and 83-252-1 had the highest average yields, while Vanderplank and 84-304-4 had the lowest. The latter genotype (84-304-4), however, died off early because of *Erwinia* infection, and no conclusions should be drawn from its performance.

The preferential ranking of genotypes was dependent on water treatments (Table 4.3). At the wetter treatments (W1-W3) there was virtually no change in the ranking and Up-to-date outperformed all the other genotypes, with the exception of Mondial which produced similar yields. At the drier treatments (W4-W5) the other genotypes yielded as well as or better than Up-to-date. Especially the genotypes 82-252-5 and 83-252-1 performed exceptionally well at the dry treatments.

TABLE 4.3: AMMI preferential ranking of genotypes compared with Up-to-date as a standard according to their marketable yields at different water treatments in spring plantings

Rank no.	Water treatment				
	W1	W2	W3	W4	W5
1	Up-to-date	Mondial	Mondial	83-252-1	83-252-1
2	Mondial	Up-to-date	Up-to-date	82-252-5	82-252-5
3	83-252-1	Late Harvest	Late Harvest	Vanderplank	Vanderplank
4	Late Harvest	83-252-1	83-252-1	Up-to-date	84-304-4
5	82-252-5	82-252-5	82-252-5	Late Harvest	Late Harvest
6	Vanderplank	84-304-4	84-304-4	84-304-4	Mondial
7	84-304-4	Vanderplank	Vanderplank	Mondial	Up-to-date

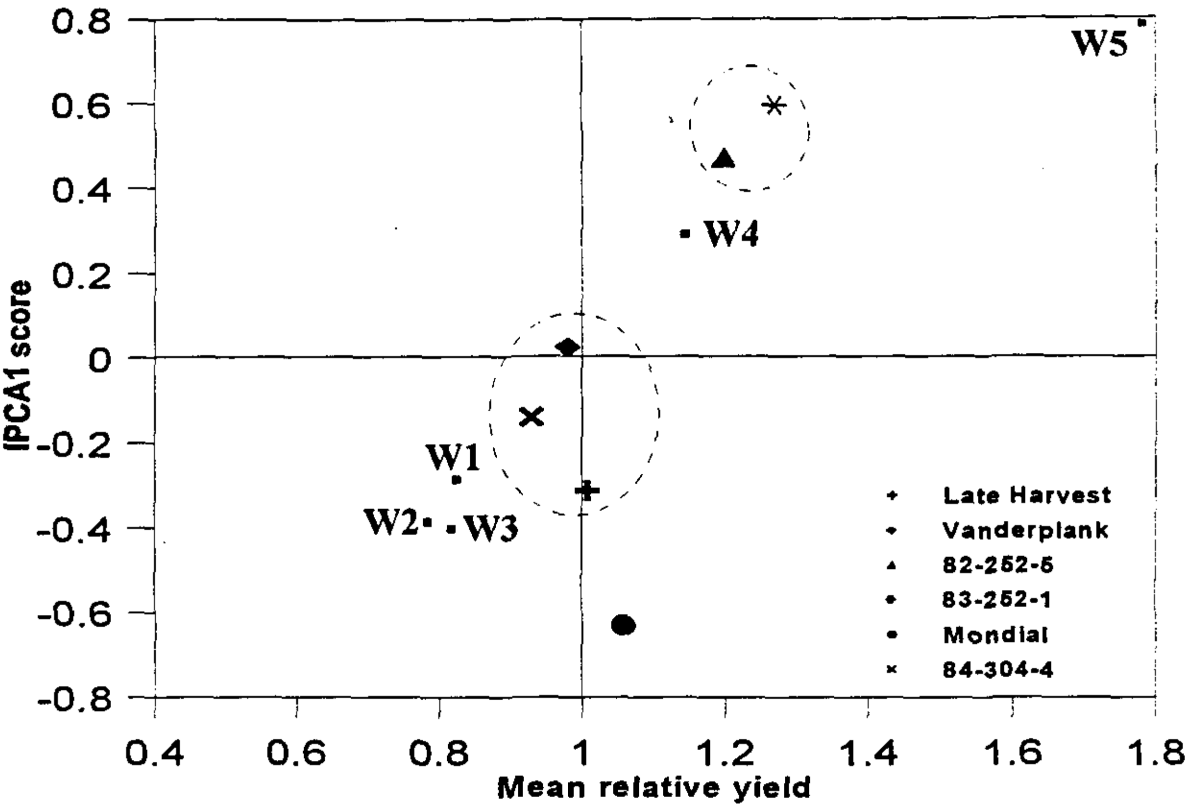


FIGURE 4.7 : AMMI IPCA1 scores and average relative tuber yields (relative to Up-to-date) of six medium potato genotypes as influenced by five levels of water during the 1992 to 1994 spring seasons

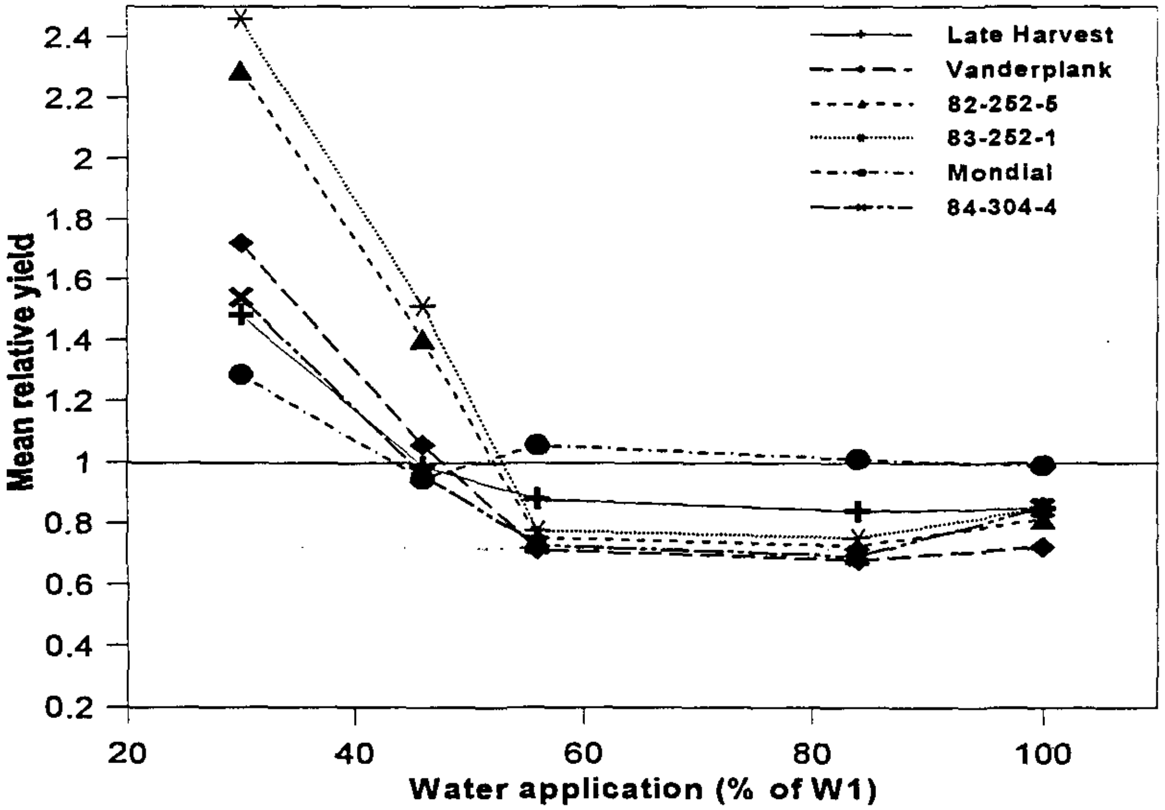


FIGURE 4.8 : Relative water-yield curves (relative to Up-to-date) of six medium potato genotypes exposed to five levels of water stress during the 1992 to 1994 spring seasons

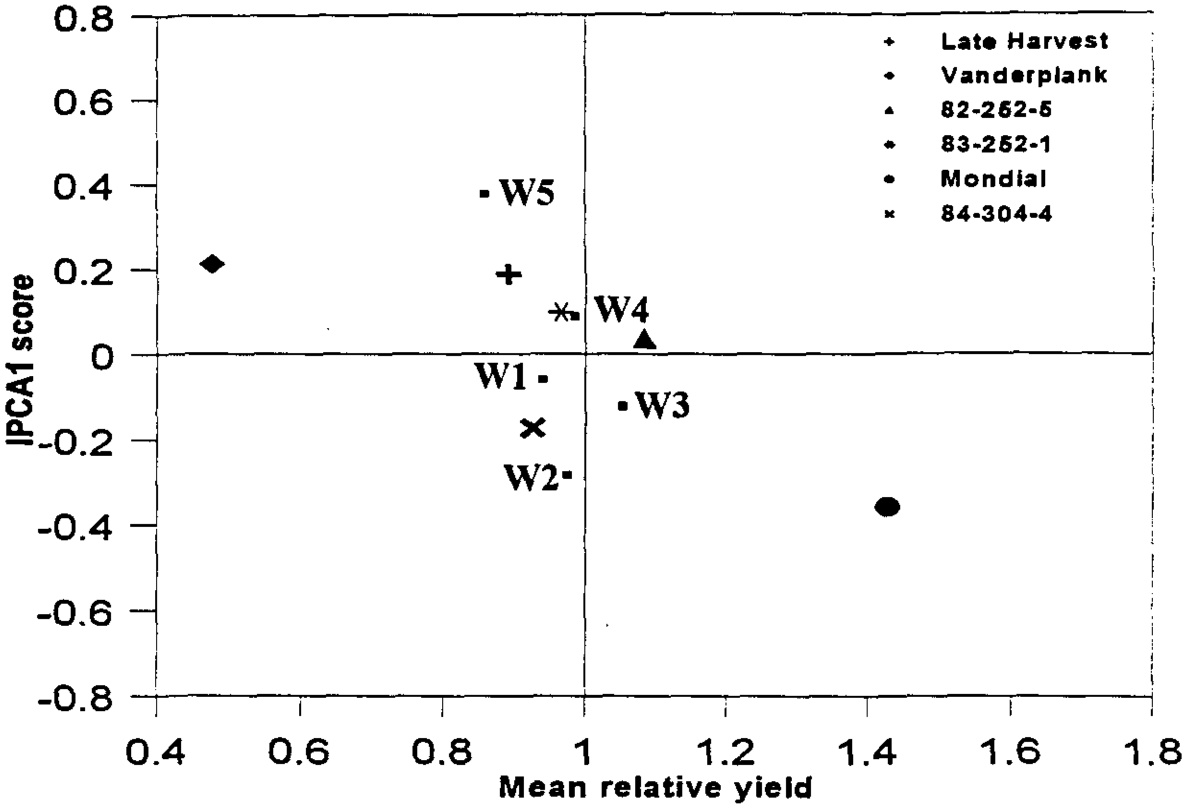


FIGURE 4.9 : AMMI IPCA1 scores and average relative tuber yields (relative to Up-to-date) of six medium potato genotypes as influenced by five levels of water during the 1993 to 1995 autumn seasons

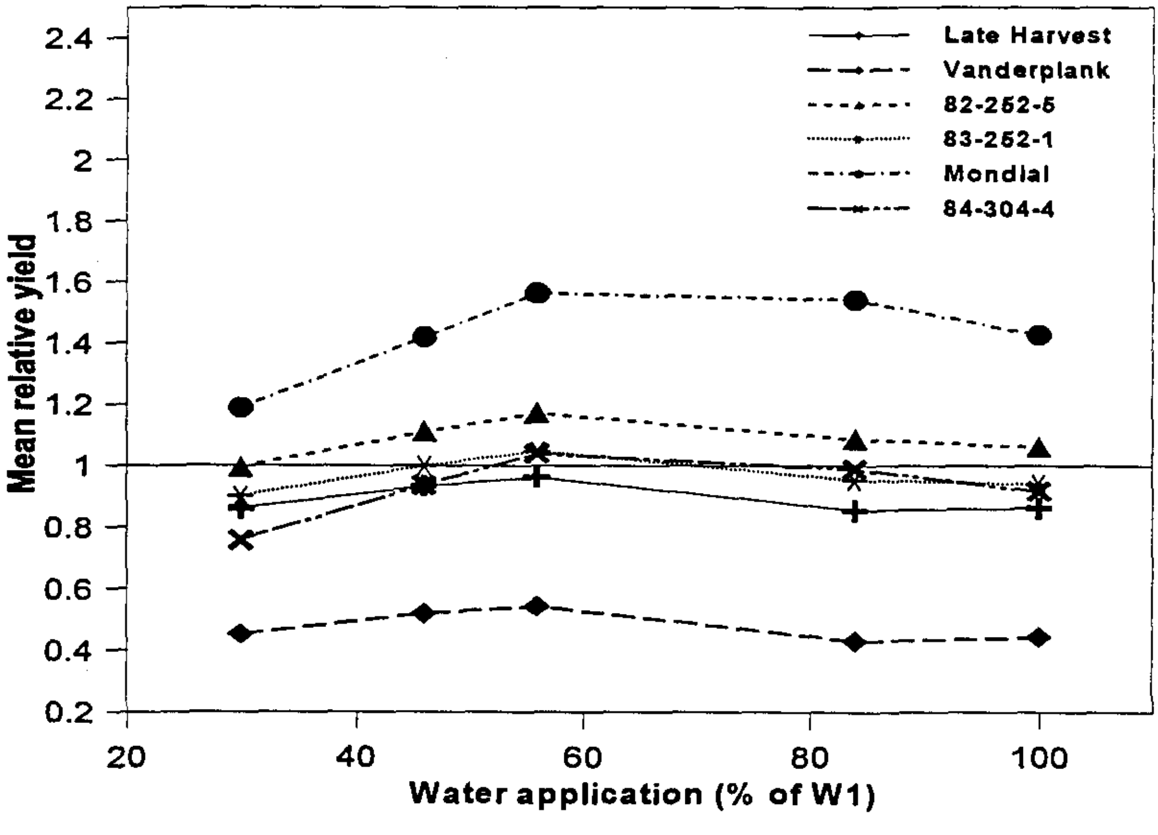


FIGURE 4.10 : Relative water-yield curves (relative to Up-to-date) of six medium potato genotypes exposed to five levels of water stress during the 1993 to 1995 autumn seasons.

For the medium-maturity genotypes the interactions between water treatments and genotypes were not significant for the autumn plantings, as was the case with the late genotypes. The main effects were, however, significant (summary of the ANOVA presented in Table B7 of the Appendix. The mean relative yield at all the water treatments grouped around one (Figure 4.9), indicating that the average yield of the genotypes did not differ much from that of Up-to-date for the same water treatment. The absence of trends over water treatments is clearly illustrated by the relative production functions (Figure 4.10). The ranking of genotypes was therefore not affected by water treatments, as was the case with the late genotypes. Mondial consistently had the highest yield and Vanderplank the lowest.

4.3.2 Tuber-size distribution

Late genotypes In general, the bulk of the total yield was made up from the yield of medium size tubers during the spring plantings (Figure 4.11). The relative proportions of the different sizes were influenced by year effects, as is clear from the size-distribution data of Late Harvest over the three spring plantings. Although the total yields were fairly stable around 50 Mg ha^{-1}, the wetter treatments had a higher proportion of large tubers in 1993 than in other years. In 1994 there was a tendency for more small tubers to be produced at all water levels; this was conspicuous for Late Harvest, and even more so for 83-363-67. The yield of small tubers was apparently not influenced by water treatments, remaining fairly constant in all genotypes. The yield of large tubers was the first to be reduced by water stress and for the most stressed treatment (W5), hardly any large tubers were produced by any of the genotypes.

The rate of decline in yield with increased water stress seems to be lower for medium than for large tubers and there are indications of genotypic differences in declining total yield with water stress. With the genotypes Late Harvest and Vanderplank, for instance, there seems to be a lower rate than for Up-to-date and Mnandi. This phenomenon is discussed later as a possible measure of drought tolerance (Chapter 9). Water stress did not result in marked differences in tuber-size distribution of genotypes, although 83-363-67 produced few large tubers for treatments drier than W2. The lowest yields were produced by 84-304-4, where population problems were encountered due to physiologically young seed tubers.

The total yields in autumn were generally only slightly lower than in spring plantings (Figure 4.12). The autumn of 1995 was, however, an exception, and very low yields were produced by all the genotypes. This was probably attributable to less solar radiation being intercepted by plants due to a cloudy season. The class A-pan evaporation for the 1995 autumn totalled ca. 400 mm, compared with the average of 525 mm for the other autumn plantings covered in this study. The proportion of large tubers appeared to be slightly lower than in the spring plantings for all genotypes. The rate of decline in total yield with increasing water stress appeared to be more gradual than in spring plantings, possibly because of the lower atmospheric evaporative demand in autumn. Genotypic differences were also not as obvious.

Medium and early genotypes Total tuber yield of all the genotypes generally declined as less water was applied (Figure 4.13). Tuber-size distribution was dependent on year effects, as was the case with the late genotypes. During the 1994 spring planting, conditions were conducive to the production of more small tubers and fewer large tubers, a phenomenon also observed for the late genotypes. The medium-size tuber yield made up the largest proportion of the total yield in all genotypes. There were definite genotypic differences in the rate of decline in total yield with increased water stress. The tuber-size distribution of genotypes was apparently not influenced differently by water stress during spring plantings, as within the same year, all genotypes followed trends similar to that of the standard cultivar (Up-to-date).

Apart from the autumn 1995 planting, when yields were very low, total yield differences between spring and autumn plantings were relatively small, except for the two early genotypes Vanderplank and 83-252-1, which had considerably lower yields in autumn than in spring plantings (Figures 4.13 and 4.14). For all cultivars, the decline in yield of large and medium tubers was more gradual in autumn than in spring plantings. The lower atmospheric evaporative demand in autumn presumably induced lower levels of plant water stress, which resulted in the production of more large and medium-sized tubers than in spring plantings.

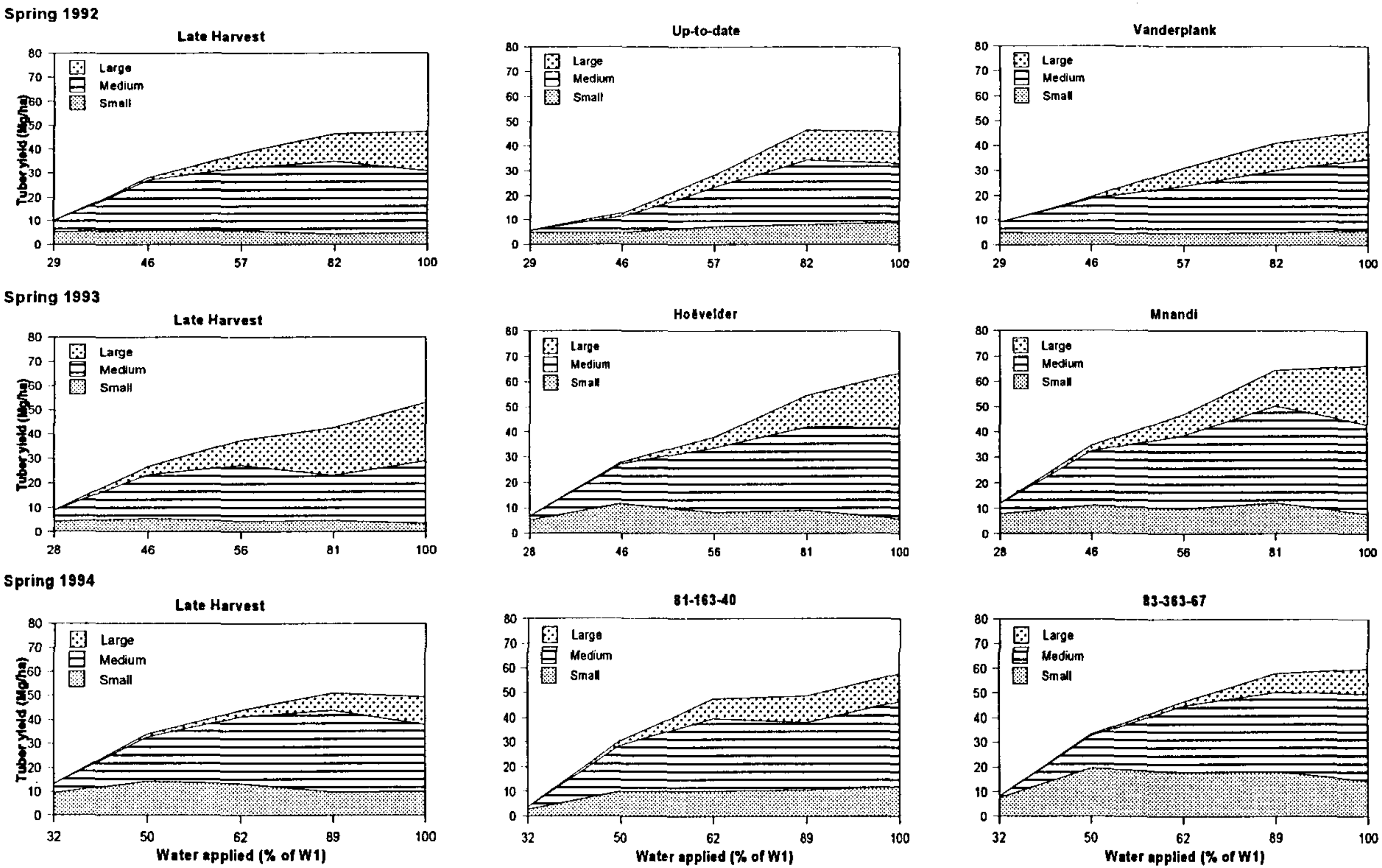


FIGURE 4.11: Tuber-size distribution of late genotypes as influenced by five water treatments in the 1992 to 1994 spring seasons. Note: X-axis not linear

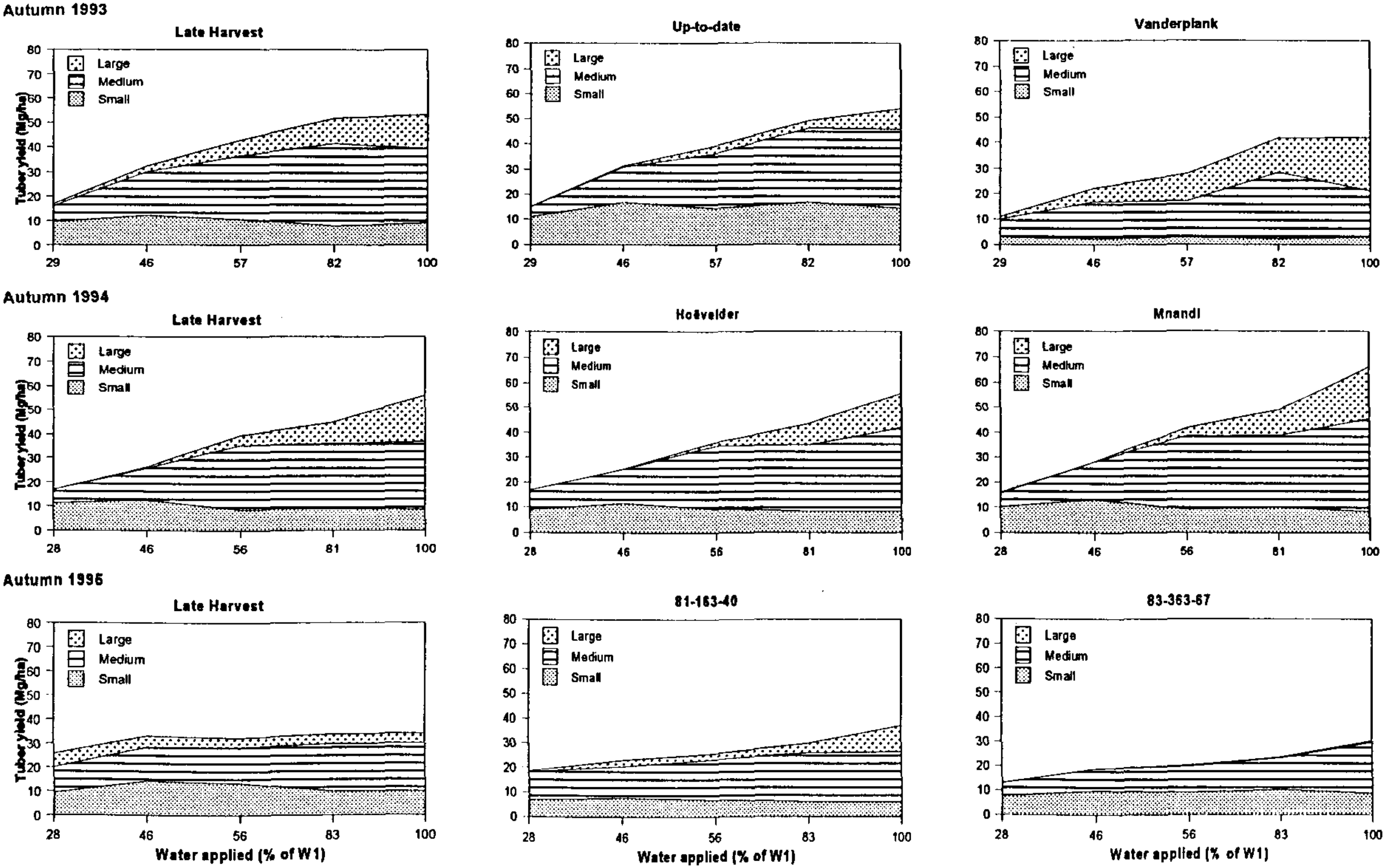


FIGURE 4.12: Tuber-size distribution of late genotypes as influenced by five water treatments in the 1993 to 1995 autumn seasons. Note: X-axis not linear

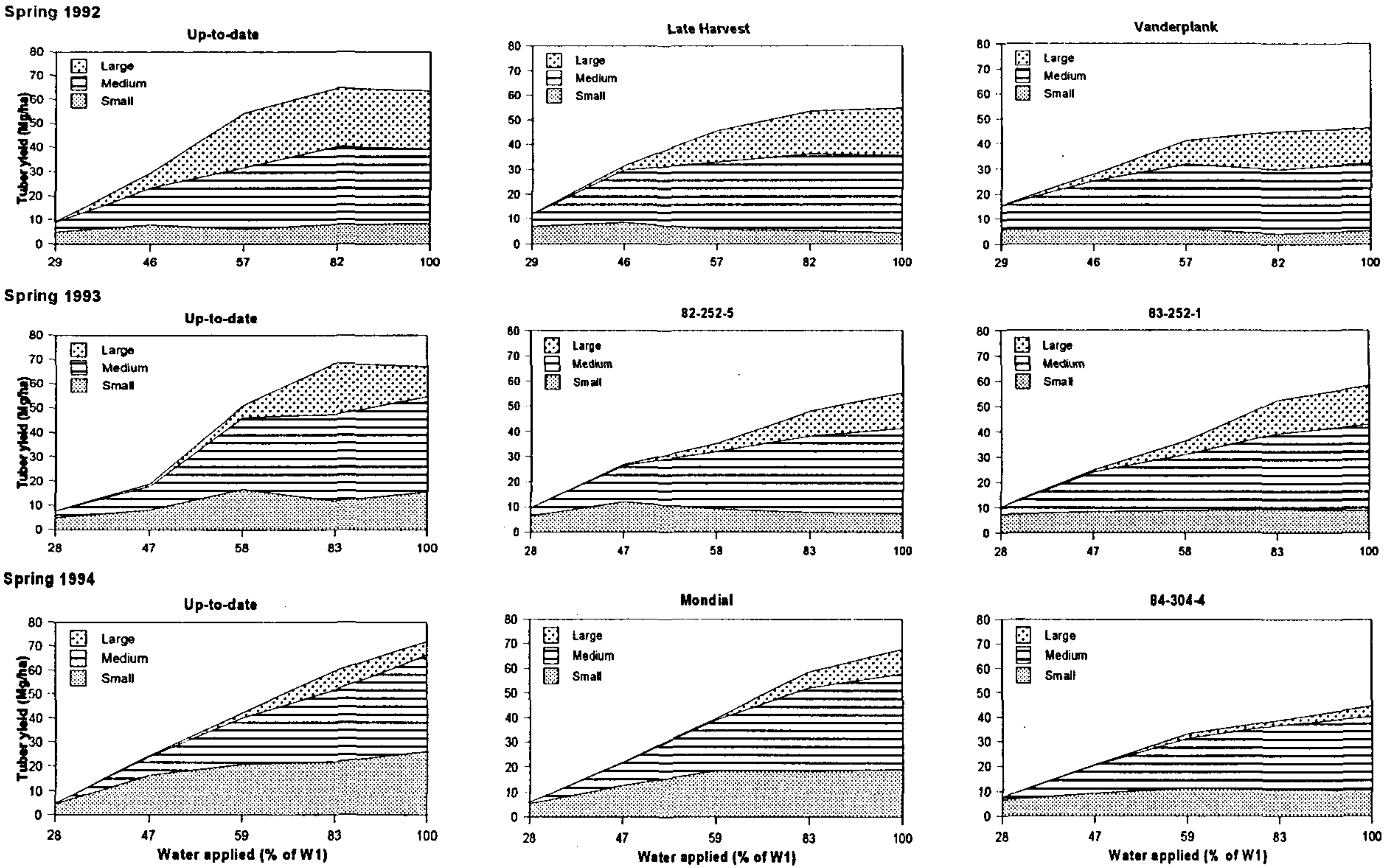


FIGURE 4.13: Tuber-size distribution of medium genotypes as influenced by five water treatments in the 1992 to 1994 spring seasons. Note: X-axis not linear

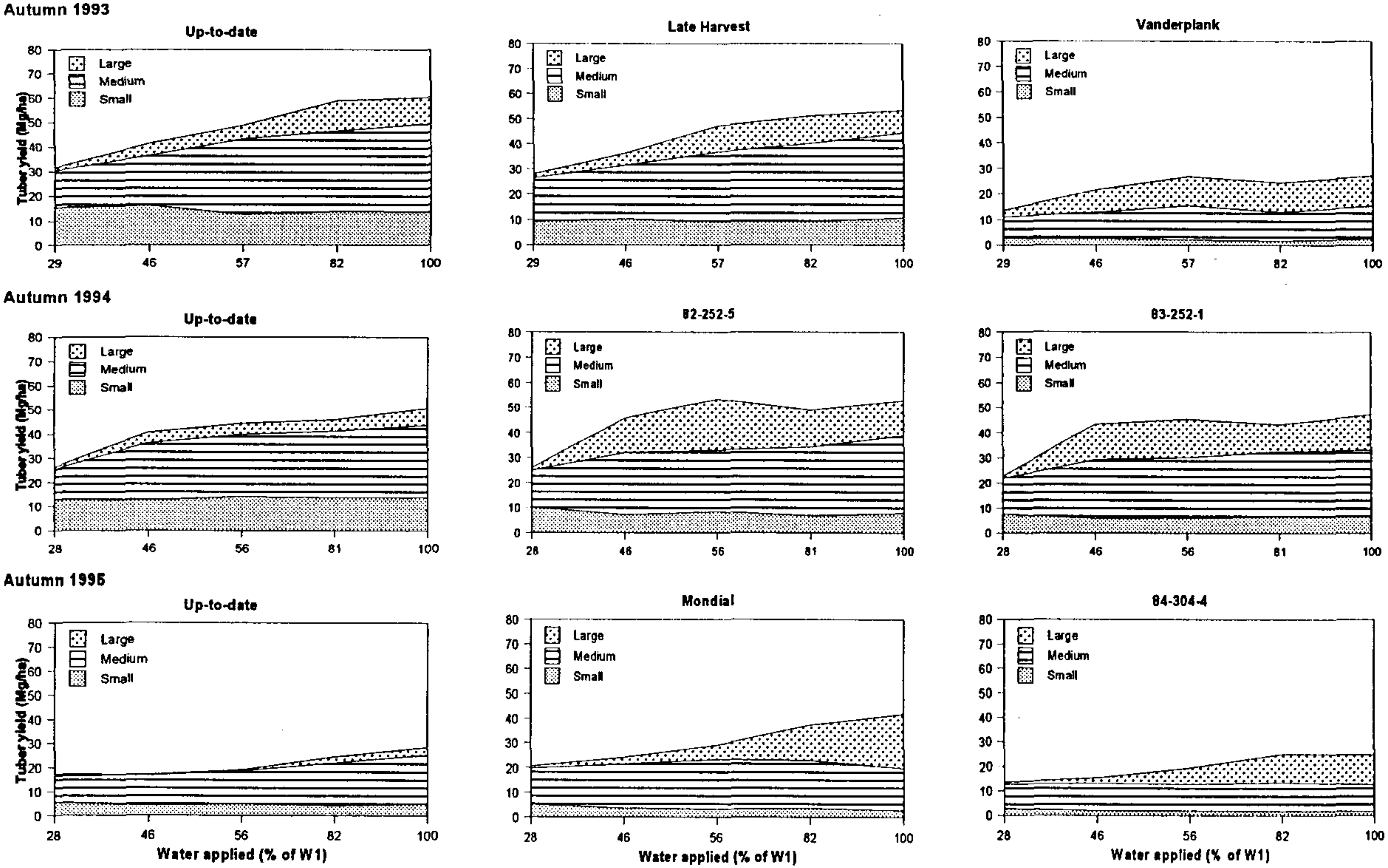


FIGURE 4.14: Tuber-size distribution of medium genotypes as influenced by five water treatments in the 1993 to 1995 autumn seasons. Note: X-axis not linear

For most of the genotypes total yield for W5 in spring plantings was more than double that in autumn. The breeding lines 82-252-5 and 83-252-1 showed almost no decline in yield of medium and large tubers when water supply was reduced from W1 to W4.

4.4 Discussion

The responses of genotypes to levels of water supply were dependent on plantings, with the effect of drought on total yield and tuber-size distribution more detrimental in spring than in autumn plantings. The yields from well watered treatments generally did not differ much between plantings (spring and autumn), with the exception of the 1995 autumn planting, when yields were very low. Levy *et al.* (1990), however, have reported substantially lower yields in autumn than in spring for subtropical conditions, essentially similar to those of Roodeplaat, resulting from decreasing temperature, day length and irradiation levels (Table 3.1). Many cultivars included in their trials were of European origin and may therefore be sensitive to the shorter autumn days. Surprisingly, in the present trials only the yields of the early genotypes 83-252-1 and Vanderplank were lower in the shorter autumn season than in spring, indicating their possible sensitivity to short day conditions.

In autumn, the ranking of genotypes according to yield was not influenced by water stress, but rather by genetic potential and adaptability to climatic conditions. Genotypes adapted to the autumn season need a capacity for early tuberization and tuber growth under high temperatures, and the maintenance of effective haulm growth (Levy *et al.*, 1990), as short days generally prevent flowering, promote tuber initiation and hasten crop maturity (Ezekiel, Perumal & Sukumaran, 1987).

Yield losses as a result of water stress were much higher in spring than in autumn plantings. In spring plantings, the effect of water stress might be aggravated by higher temperatures (Levy *et al.*, 1990) and, possibly, by the higher atmospheric evaporative demand as summer sets in (Trebejo & Midmore, 1990). In spring plantings genotypic differences in response to drought were recorded for both maturity classes. In the wetter treatments the ranking of genotypes remained unchanged and yield was dependent on genetic potential, but the ranking changed as stress increased in both maturity classes. Late Harvest, the standard cultivar in the late maturity class, was one of the better performers under drought conditions. This agrees with the findings of Van der Mescht *et al.* (1992), who used biochemical screening techniques to classify the drought tolerance of potato genotypes. Up-to-date, the medium standard cultivar, was one of the more drought-sensitive cultivars, as it had the largest reduction in yield due to drought. In a study by Jefferies & MacKerron (1993), Up-to-date was also among the cultivars that showed the highest degree of yield reduction as a consequence of drought. The medium to late genotypes had the highest yield potentials, while the early cultivar Vanderplank had the lowest average yields. The genotype 84-304-4 performed unsatisfactorily in both plantings due to external factors and should be further evaluated before any conclusions can be drawn regarding the effect of water stress on its performance.

Certain of the genotypes that had high yield potentials under optimal conditions (e.g. Up-to-date and Mondial) produced the lowest yields when stressed. This often happens as most of the adaptation traits that favour survival under stress conditions tend to reduce potential yields (Begg & Turner, 1976 according to Levy *et al.*, 1990). On the other hand, some of the genotypes that produced the lowest yields under optimal conditions, had the highest yields when stressed (e.g. Late Harvest). These findings contradict the conclusion of Jefferies & MacKerron (1993) that there is limited capacity for improvement in drought tolerance through breeding, other than through improvements in potential yield. In some cases high yield potentials did compensate for sensitivity to drought. Hoëvelder is a typical example in this regard: it showed sensitivity to drought but, because of its high yield potential, produced the same or higher yields than Late Harvest for all water treatments, with the exception of W5. Mnandi had a very high yield potential in summer, while also showing drought tolerance similar to that of Late Harvest. Drought tolerance is not related to maturity class, as some genotypes representative of all the maturity classes showed the ability to withstand drought. This suggests that drought tolerance is also not only attributable to drought escape by early genotypes, as is often reported in literature.

The yield of medium, but especially large tubers, was influenced negatively by water stress. This trend was also recorded by MacKerron & Jefferies (1988), who reported a downward shift in size distribution because of drought. Medium-sized tubers made up the bulk of total yield in all maturity classes and plantings. The negative effects of water stress on size distribution were less severe in autumn plantings, as was the case with total yield. Tuber size appeared not to be influenced differently by water stress in most of the genotypes. However, the two genotypes 82-252-5 and 83-252-1 were able to maintain high yields of medium and large tubers down to the W4 water supply level.

The physical yield of small tubers was not increased by water stress. In the drier treatments the yield of small tubers made up a greater proportion of the total yield, due to the fact that the medium and large yield decreased.

Some of the variation in the proportion of large to medium tubers may not only be attributable to external factors such as drought, but may also be as a consequence of the arbitrary boundaries that were set for the separation of classes. The difference between medium and large tubers, especially, may have caused some variation as tubers of 249 g were considered to be medium, while tubers of 250 g and heavier were recorded as large. In small-plot trials such as these, a few tubers just below or above the cut off margin may lead to a total distortion of the data, as the large tubers contribute significantly to the total mass.

4.5 Conclusions

The negative effects of drought on tuber yield and size distribution were more severe in spring than in autumn plantings, presumably because of the higher atmospheric evaporative demand and higher temperatures in spring plantings. The ranking of genotypes according to tuber yield was dependent on the water regime in spring plantings, while in autumn the ranking was unchanged and mainly determined by the genetic potential of genotypes. This implies that the selection of genotypes by the potato producer should be based on the availability of water in spring, but not in autumn plantings. Drought-sensitive genotypes, such as Up-to-date, Mondial and 81-163-40 should be avoided where water stress is expected during spring plantings.

In the late-maturity class Late Harvest, Mnandi and Hoëvelder perform best when water supply is limited. Mnandi will also produce high yields with ample water. In the medium-maturity class Vanderplank, 83-252-1 and 82-252-5 should produce good yields under drier conditions, while Up-to-date and Mondial are the most sensitive to limited water supply. When water is non-limiting the latter two cultivars have high yields and should be used.

Water stress lowered the yield of large and medium tubers in all genotypes, but genotypic differences were small. The effect of water stress on tuber size distribution and total tuber yield was more detrimental in spring plantings. The disadvantageous downward shift in tuber size because of drought may be of lesser concern to seed producers, who strive for tuber sizes of between 50 g and 120 g (small to medium), but it should be kept in mind that total tuber yield will also be reduced as a consequence of water stress.

In the current study, local potato genotypes have for the first time been characterised according to their performance at different levels of water supply. This should assist the potato producer in the selection of genotypes most suitable for his farming conditions, considering the growing season and available water supply.

CHAPTER 5

THE EFFECT OF WATER REGIMES ON INTERNAL TUBER QUALITY

5.1 Introduction

Water stress affects both internal and external potato tuber quality, aspects that have received considerable attention in research programmes (Van Loon, 1986; Adams & Stevenson, 1990; Ojala *et al.*, 1990; Jefferies & MacKerron, 1993; Shock, Holmes, Stieber, Eldredge & Zhang, 1993; Trebejo & Midmore, 1990). Interrupted irrigation during the tuber bulking phase may lead to lower external quality due to disorders such as secondary growth, growth cracking and knobby tubers (Adams & Stevenson, 1990). Two important internal quality characteristics commonly affected by water supply are tuber dry matter and reducing sugar content.

Tuber dry matter and reducing sugar content are especially important if tubers are intended for processing: The yield of crisps, a processed tuber product, is dependent on the dry matter content of the tubers, since crisping is a dehydration process (Logan, 1989). Lower dry matter percentages therefore directly relate to losses in income. Chip colour, one of the most important quality attributes in the potato processing industry (Orr & Janardan, 1990), depends on the reducing sugar content of tubers. Tubers containing high concentrations of reducing sugars produce fries and crisps that are unacceptably dark in colour.

The dry matter content of tubers at harvest is influenced by various factors during the growing season. Dry matter content tends to increase progressively during the growth of the crop to reach maximum values at maturity (Jewell & Stanley, 1989; Ojala *et al.*, 1990), but the pattern of increase varies greatly between crops and years, and the final value at harvest is influenced by cultivar, cultural practices and the environment (Jefferies *et al.*, 1989). In drought-stressed crops the dry matter content of tubers is usually increased (Marutani & Cruz, 1989; Trebejo

& Midmore, 1990; Jefferies & MacKerron, 1993), because water stress affects tuber water content to a greater extent than dry matter accumulation (Jefferies *et al.*, 1989). Ojala *et al.* (1990) observed reduced tuber relative densities as a result of interrupted irrigation, while the effect of declining irrigation on relative density was small and inconsistent (Miller & Martin, 1987b).

Dry matter accumulation in tubers is also dependent on temperature during the growing period of the crop. It is favoured by increasing temperatures up to an optimum of about 18°C (Van Heemst, 1986). At higher temperatures the partitioning of dry matter to the tubers is inhibited (Van Heemst, 1986) and the dry matter content of tubers is therefore reduced (Levy, 1984). According to Jefferies *et al.* (1989) variations in tuber dry matter content are best accounted for by a regression model that is a function of soil-water deficit and the accumulation of thermal time above a base of 0 °C from the time of emergence. They reported that increasing temperatures and soil-water deficits favoured higher dry matter contents. However, this model is based on studies in a temperate climate and may not be applicable to hot climates, as Jefferies *et al.* (1989) have pointed out.

The browning of potato chips occurs as a result of non-enzymatic reactions, involving reducing sugars and amino acids, the so-called Maillard reaction (Iritani & Weller, 1977; Owings *et al.*, 1978). Glucose is considered the most important reducing sugar in determining chip fry colour (Brown *et al.*, 1990; Coleman *et al.*, 1993; Coles, Lammerink & Wallace, 1993).

Under normal growing conditions the levels of reducing sugars fall as the crop matures (Iritani & Weller, 1977; Jewell & Stanley, 1989; Richardson, Davies & Ross, 1990a; Richardson *et al.*, 1990b). In some cases abnormally high sugar accumulation occurs in tubers because of unfavourable conditions during growth of the potato plants. These conditions include a lack of soil water, high fertiliser applications late in the growing season, premature vine-death and excessively high or low temperatures (Miller 1975, in Jewell & Stanley, 1989; Owings *et al.*, 1978; Sowokinos, 1990).

Reducing sugars start to accumulate in tubers at temperatures below 10 °C (Dogras, Siomos

& Psomakelis, 1991) as a result of the conversion of starch to free reducing sugars (Harris, 1978; Sowokinos, 1990). High mid-season soil temperatures are reported to increase sugar-end tubers (Kincaid, Westermann & Trout, 1993). Kincaid *et al.* (1993) were able to lower high soil temperatures by increasing the frequency of irrigation, but the amount of irrigation did not affect soil temperature or tuber quality. Logan (1989), however, could not find any differences in reducing sugar content as a result of different irrigation frequencies.

The mechanisms responsible for stress-induced sweetening of potato tissue are still to be explained at the molecular level. This is not surprising, since the production of free sugars in cells is not regulated by a single factor (Sowokinos, 1990).

Little is known about the effects of environmental conditions and cultivation practices on tuber relative density and reducing sugar content of South African potato cultivars. Although aspects such as chip colour are only of major concern to the processing industry, tuber relative density is also important to the table potato market, as it gives a general indication of tuber keeping quality. In this study the effects of different soil-water regimes on tuber relative density and chip colour were determined for some local potato genotypes in both spring and autumn plantings.

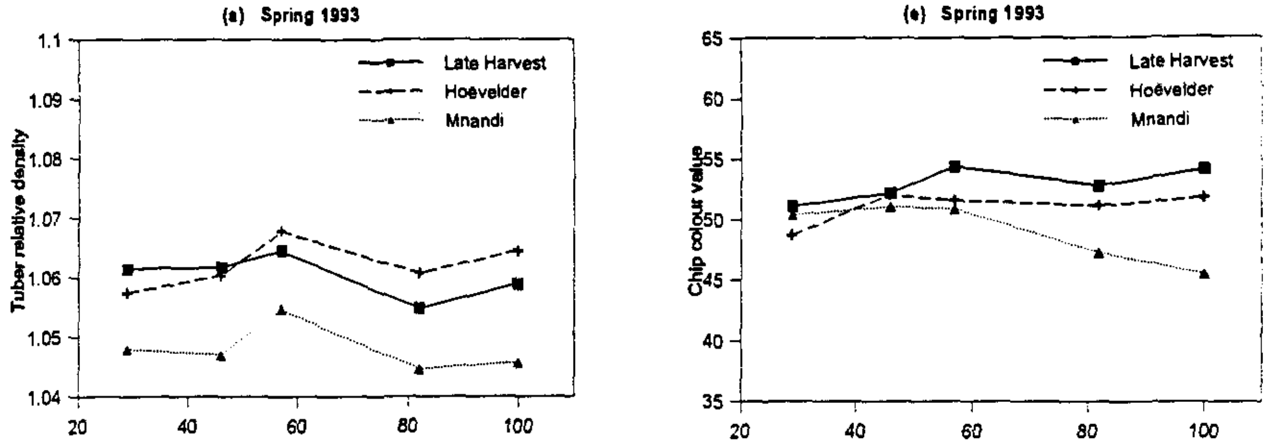
5.2 Materials and methods

Observations on quality aspects were made on the tubers obtained from irrigation trials carried out during the spring 1993 to autumn 1995 plantings. Cultivation practices and treatments applied in the trials are fully described in Chapters 3 and 4. After harvest, the tubers were graded into different size classes and weighed. Ten medium-sized tubers from each plot were randomly selected and checked for external defects. The samples were weighed in air and water, and the relative densities calculated by dividing the mass in air by the difference between the masses measured in air and water (Logan, 1989; Kincaid *et al.*, 1993). Five slices (1.5 mm thick) were cut from the stem-ends of each of the ten tubers. The slices were briefly rinsed in water and blotted with towels before being fried in vegetable oil at initial temperatures of 190 °C. Frying was continued for approximately 3.5 minutes, until bubbling subsided and the chips were crisp (Ewing, Senesac & Sieczka, 1981). The fried chips were drained and allowed to cool, before they were placed in brown paper bags and gently crushed. A Model D25L-2 Hunterlab colorimeter was used for chip colour determinations according to the method described by Scanlon, Roller, Mazza & Pritchard (1994), with the exception that the chip samples were crushed before measurement.

5.3 Results

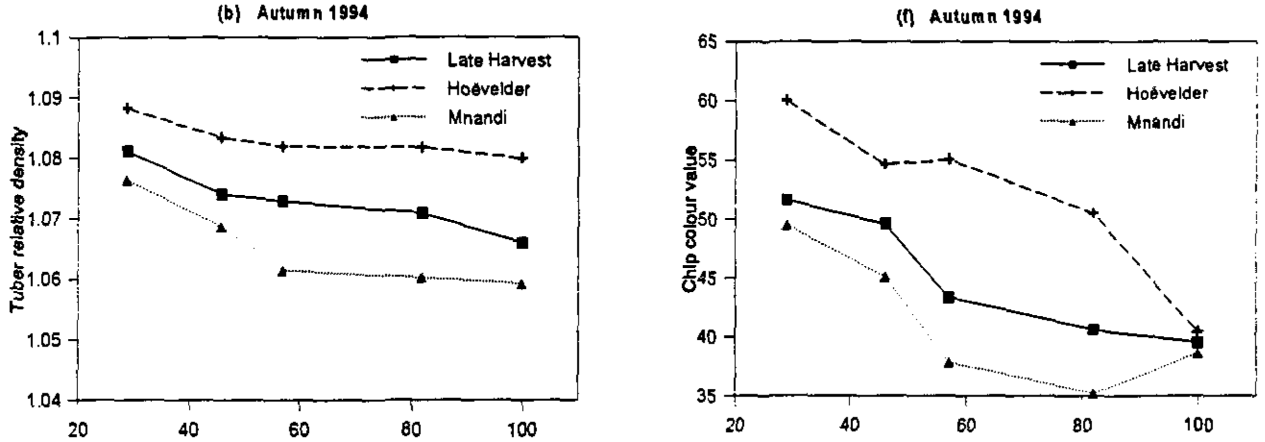
Tuber relative density

Results for late and medium genotypes are presented separately in Figures 5.1 (a-d) and 5.2 (a-d). Marked seasonal differences in tuber relative densities were observed. In spring plantings tuber densities were generally lower than in autumn (for the same genotypes). No clear trends were observed as a result of water treatments in spring, while in most autumn plantings tuber densities decreased with increase in water supply. There were no interactions between genotypes and water treatments (Tables B8 and B9 of the Appendix), suggesting that genetic characteristics played an overriding role, since the ranking of genotypes according to their densities remained almost the same, independent of water treatment and planting. Of the late genotypes only Hoëvelder, a processing cultivar, had higher tuber densities than Late Harvest, the standard. Mnandi consistently had very low tuber densities, especially in the spring planting. Small differences were observed between genotypes in the medium maturity class. The two breeding lines intended for processing, 82-252-5 and 83-252-1, which were expected to produce high tuber densities, did not differ from Up-to-date in either planting. Unlike the tendencies in other autumn plantings, there was no trend over water treatments in the 1994 autumn planting, but tuber densities were consistently high for that planting. Mondial was the only cultivar that showed consistently lower tuber densities than the standard, Up-to-date.



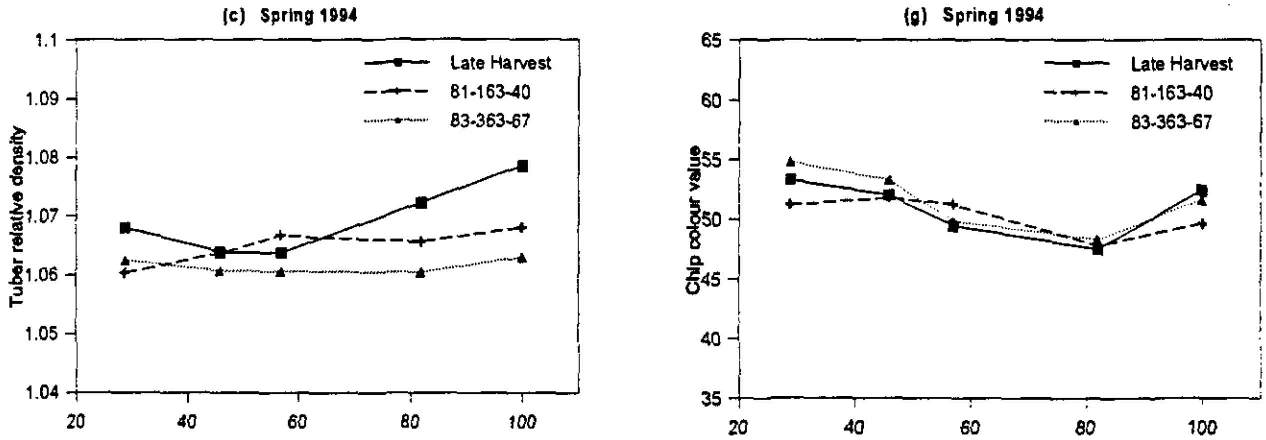
(a) Spring 1993

(e) Spring 1993



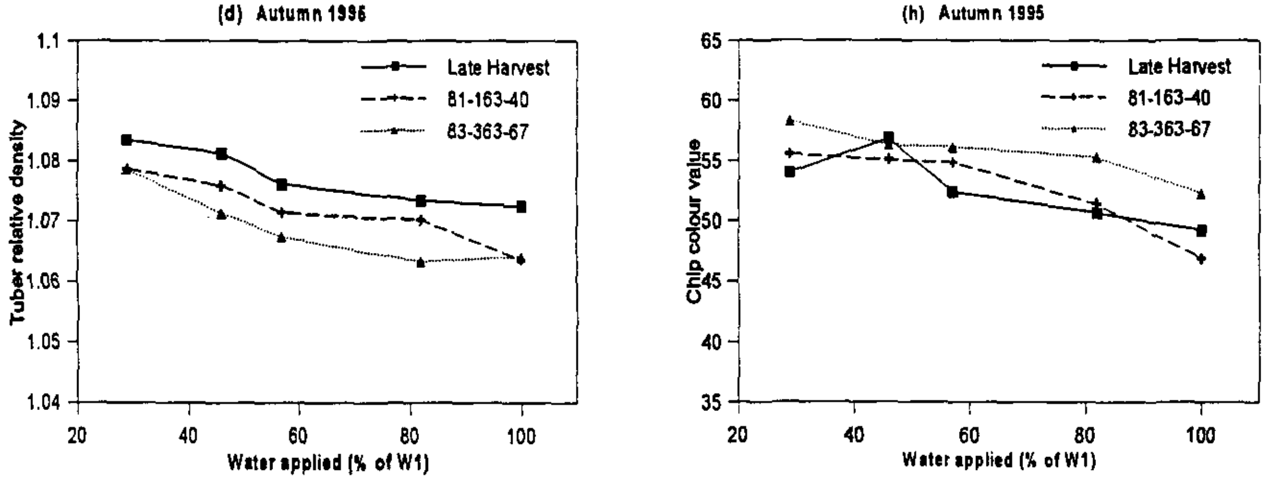
(b) Autumn 1994

(f) Autumn 1994



(c) Spring 1994

(g) Spring 1994



(d) Autumn 1995

(h) Autumn 1995

FIGURE 5.1 : **The effect of five water regimes on tuber relative densities (a-d) and chip colours (e-h) of late genotypes in spring and autumn**

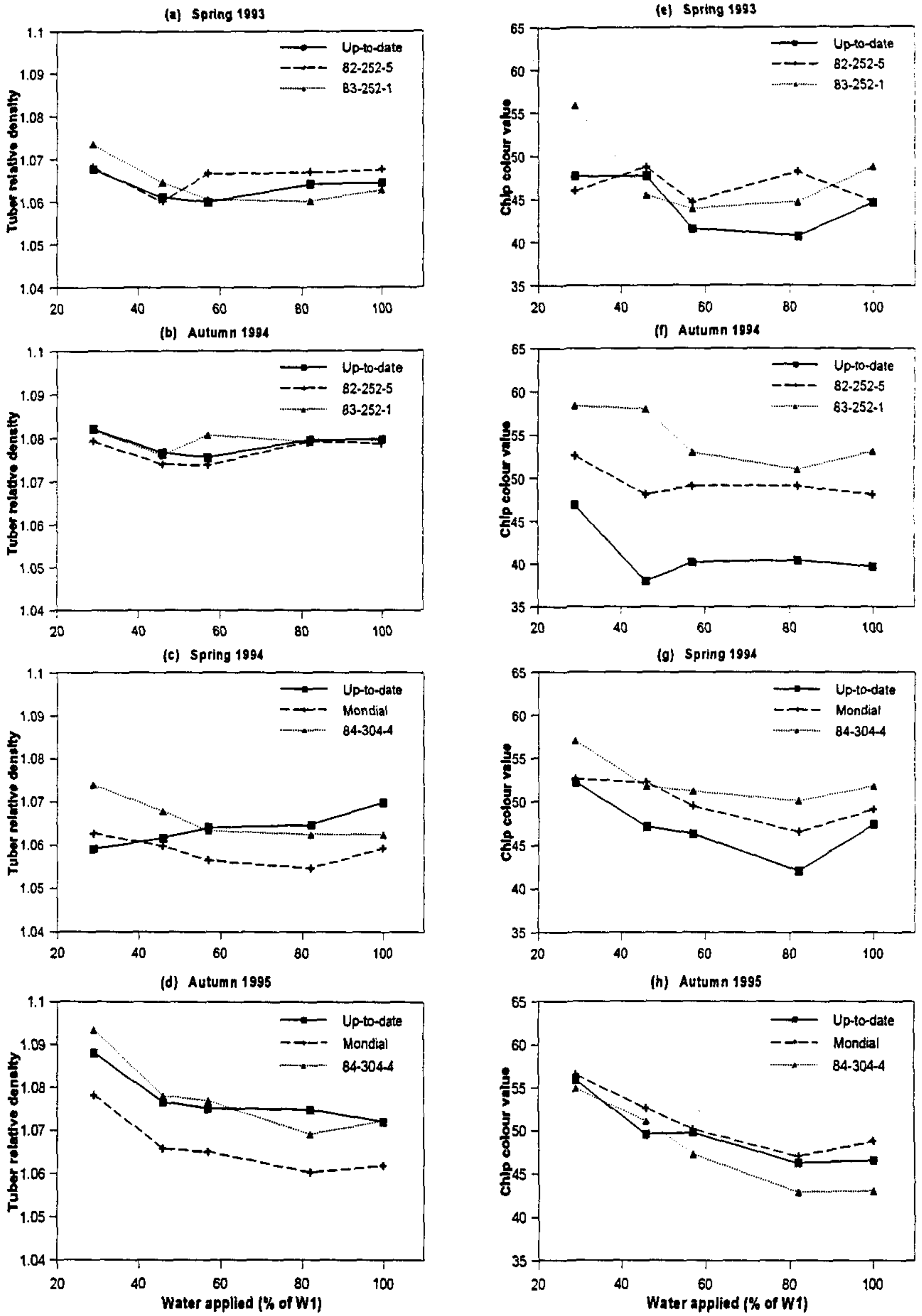


FIGURE 5.2 : The effect of five water regimes on tuber relative densities (a-d) and chip colours (e-h) of medium genotypes in spring and autumn

Chip colour

Chip colour results are presented in Figures 5.1 (e-h) and 5.2 (e-h) for the late and medium maturity classes, respectively. Chip colour values of 50 and higher are considered acceptable for processing. In most of the trials, with the exception of one spring planting, trends in response to irrigation treatments were evident. These trends were more pronounced for the autumn plantings, but the interactions between genotypes and water regimes were not significant for any planting (see Tables B10 and B11 of the Appendix for summarised ANOVAs). For both the late- and medium-maturity classes chip colour generally deteriorated with an increase in water supply. Most of the genotypes produced acceptable chip colours in the drier treatments in all plantings. In autumn plantings chip colours were not always better than in spring for the same irrigation treatments, as was the case with relative densities. Chip colour results of genotypes were not stable over plantings: the best chip colours were not produced by the same genotypes in spring and autumn plantings.

5.4 Discussion

Trends regarding tuber relative densities were dependent on seasonal effects. In autumn plantings the tuber relative densities of all the genotypes generally increased as less water was applied. This trend is expected as the water content of tubers is dependent on the water content of the surrounding soil (Jefferies *et al.*, 1989) and agrees with the results obtained by Marutani & Cruz (1989), Trebejo & Midmore (1990) and Jefferies & MacKerron (1993). The absence of trends in this study in tuber relative densities as a result of water treatments in the spring plantings is unexpected and contrary to most reports in the literature.

High ambient temperatures are known to have negative effects on tuber dry matter content (Hartz, 1978; Van Heemst, 1986), and therefore on tuber relative density: Yamaguchi, Timm & Spurr (1964) (according to Kincaid *et al.*, 1993) have found that specific gravity and starch content were highest and sugar content lowest when potatoes were grown at soil temperatures between 15 °C and 24° C. According to Jefferies *et al.* (1989) and Van Heemst (1986) optimum air temperatures for dry matter allocation to the tubers are between 18 and 20 °C. Higher air and soil temperatures in spring plantings may therefore explain the lower tuber densities observed in these plantings.

Soil temperatures were not recorded during the execution of the present study, but are known from literature to be a function primarily of air temperature and radiation (Kincaid *et al.*, 1993). The average air temperatures recorded during the tuber bulking phase were between 2 °C and 7 °C warmer in spring plantings (October to December) than in autumn (April to May) (see Figure 3.1). Air temperatures during the bulking phase were therefore higher than the optimum on most days in the spring plantings, while in autumn it was only the case during the early tuber bulking phase (first part of April) of some plantings.

Soil temperatures are to a lesser extent also influenced by factors like shading of the soil surface and soil-water content (Kincaid *et al.*, 1993). In the wetter treatments it was expected that higher soil-water content and a higher degree of soil cover by larger crop canopies would have beneficial effects on soil temperature in spring plantings. This does not seem to be the case, as the relative densities of wetter treatments were no better than those of dry treatments. Kincaid *et al.* (1993) found that both amount and frequency of irrigation influenced soil temperatures, but that frequency had the largest effect. High frequency irrigation maintained lower soil temperatures, probably due to increased evaporation from the soil surface. In the present study the frequency of irrigation was the same for all treatments (only the amount of irrigation differed), which may explain the absence of trends in spring plantings. In autumn the temperature effect was negligible due to lower ambient temperatures during tuber bulking, and tuber relative densities were mainly determined by water supply.

Genotypic differences played an overriding role in the ranking of genotypes according to tuber relative density, independent of the planting and water regime applied. The relative densities of genotypes were also not influenced differently by water stress.

The effect of water stress on chip colour is still not clear. The results of the present study suggest that chip colour was apparently never affected negatively by water stress in any of the genotypes and plantings. This is in contrast to most published reports of darker stem-end (basal end) chip colours in water stressed environments (Owings *et al.*, 1978; Kincaid *et al.*, 1993; Shock *et al.*, 1993). Variable results between seasons and localities have, however, often been reported in the literature: Richardson *et al.* (1990a), for example, were not able to relate reducing sugar content to any factor other than harvest date, despite a range of environmental conditions and management practices, which included differences in soil temperature and total rainfall; Kincaid *et al.* (1993) did not consistently record better chip colours for wetter treatments, although high-frequency irrigation seemed to improve chip colour. The high frequency of irrigation in the present trials, even though application amounts were small, may therefore have improved the chip colours resulting from the dry treatments to the extent that they were similar to that resulting from the wet treatments in spring plantings.

High temperatures during tuber development are known to increase reducing sugar content (Owings *et al.*, 1978) and therefore to produce darker chips. In the spring plantings, the detrimental effects of high temperatures on chip colour appear to be balanced by the beneficial effects of regular irrigation. It also appears that reducing sugars start to accumulate at higher temperatures than those at which tuber relative densities are influenced negatively. The results are therefore that chip colours of water stressed treatments were no worse than those of unstressed treatments.

In autumn plantings, temperatures were generally lower during the tuber bulking phase, compared to spring plantings. Since chip colour generally improved with increasing water stress, the effect of high temperature on chip colour was clearly not a factor. As this trend is in contrast to most published findings, the possible effects of low temperatures experienced at the end of the season in the case of wet treatments should be investigated. Low temperatures late in the growing season have been reported to induce higher concentrations of reducing sugars in tubers (Miller, 1975 according to Jewell & Stanley, 1989). The reaction is similar to cold sweetening under low temperature storage (Gawad, Omer & Ahmed, 1990; Dogras *et al.*, 1991). Reducing sugars only start to accumulate at temperatures below 10 °C. Although in the present study minimum air temperatures dropped below 10 °C from the beginning of April, mean air temperatures lower than 10 °C were never experienced in autumn (Figure 3.1). In the absence of soil temperature measurements, only speculations can be made on the effect water regimes would have had on the micro climate, and therefore also on the soil temperature. It is likely that the lowest soil temperatures occurred at the wetter treatments, due to factors such as the higher thermal conductivity of wet soils, greater evaporative cooling and the fact that the soil surface was more completely covered by the canopies of unstressed plants, which reduced the portion of direct solar radiation absorbed by the soil surface. These lower soil temperatures may have resulted in the darker chip colours experienced in the case of wetter treatments.

Plant nutrition, especially the supply of nitrogen, is known to influence aspects of internal tuber quality, such as tuber relative density. Higher rates of nitrogen usually reduce relative density (Logan, 1989). In this study all water regimes received the same fertilisation programme and there is a possibility that some nutrients were supplied in excess or at sub-optimum levels for high quality. Differences in the rate of nutrient uptake could also be responsible for seasonal differences in tuber quality observed.

5.5 Conclusions

Tuber internal quality was dominated by temperature effects in both plantings. In spring plantings no trends with regard to tuber relative densities were observed, mainly because of the negative effect of high temperatures on dry matter content. In autumn plantings the dry matter content of tubers was increased with increasing water stress, as was expected. Genotypes did not respond differently to water stress.

Chip colour also showed no response to water stress in spring plantings, presumably as a consequence of high temperatures and the moderating effect of high frequency irrigation. In autumn plantings, expectations arising out of literature, of chip colour deterioration with increasing water stress were not realised. In fact, the contrary was true. The frequent application of water probably helped to cool down the soil during the tuber bulking phase in autumn, with temperatures of soils in wet treatments probably being lower than those of the dry treatments. Low-temperature sweetening, a familiar phenomenon encountered in cold storage, thus apparently occurred in the wet treatments, resulting in darker chips. Genotype X water interactions were not significant, indicating that although main effects were significant, genotypes did not respond differently to water treatments.

These results show a conflict between the highest tuber yield and best tuber quality, as the treatments that produced the highest tuber yield generally produced the lowest tuber quality. Producers will therefore have to balance their irrigation scheduling to find the best compromise between highest tuber yield and quality. In this study the intermediate water regimes (W3 to W2) seemed to provide the best compromise between high yield and good tuber quality.

For future water-use studies it is recommended that soil temperatures and the nutritional status of plants should be monitored in order to quantify their complicating effects on internal tuber quality.

CHAPTER 6

THE USE OF PHYSIOLOGICAL PARAMETERS IN SCREENING FOR DROUGHT TOLERANCE

6.1 Introduction

Drought stress is recognized as a major constraint to potato production (Van Loon, 1981; Jefferies, 1983a; Dwelle, 1985; Van Loon, 1986). Tuber yield is determined by the interaction of a number of physiological processes such as photosynthesis, leaf expansion, leaf senescence, tuber initiation, and the partitioning of assimilates (Schapendonk *et al.*, 1989), all of which are affected by water stress, generally resulting in lower tuber yields (Coleman, 1986).

Stomatal closure in response to water stress reduces the rates of transpiration and photosynthesis, which may lead to decreased yield. The stomata of potato plants are reported to close at relatively high leaf water potentials compared to other crops (Van Loon, 1981), and reductions in stomatal conductance caused by water stress have frequently been reported for potatoes (Rutherfoord & De Jager, 1975; Dwelle, 1981a; Dwelle 1985; Bansal & Nagarajan, 1986; Vos & Groenwold, 1988; Ezekiel, Perumal & Sukumaran, 1989). In fact, stomatal resistance has been found to be a sensitive indicator of water stress in many crops, including potatoes (Rutherfoord & De Jager, 1975; Oosterhuis & Walker, 1987) and is also a promising aid in screening for drought tolerance in potato genotypes (Wilcox & Ashley, 1982).

The photosynthetic process has been found to be very sensitive to water stress in crops such as maize, and measurements of photosynthetic rate have given a good indication of water stress (Ceulemans *et al.*, 1988). The influence of water stress on the photosynthetic rate of potatoes has been investigated thoroughly (Munns & Pearson, 1974; Shimshi *et al.*, 1983; Dwelle, 1985, Vos & Groenwold, 1989). Although stomatal conductance responds earlier to water stress than photosynthetic rate, photosynthesis has also proved to be a good indicator of water stress in potato plants (Bodlaender *et al.*, 1986; Van Loon, 1986; Vos & Groenwold, 1989). Marked differences in assimilation rate have been recorded between genotypes and plantings (Dwelle *et al.*, 1981; Moll, 1983). However, attempts to correlate stomatal conductance (or resistance) and photosynthetic rate with tuber yield have not been very successful. The reason for the poor correlations is that tuber yield is determined not only by the photosynthetic rate of single leaves, but also by factors such as total canopy assimilation, and the partitioning of assimilates to different plant organs (Dwelle *et al.*, 1981). However, in spite of the poor correlations sometimes recorded between short-term photosynthetic rate and yield, high photosynthetic rates are nonetheless essential to achieve high yields (Dwelle, 1985).

Despite the above mentioned reservations, various authors have investigated single-leaf photosynthetic rate as a screening method for drought tolerance in potato plants: Sukumaran *et al.* (1989), for example, reported drought-induced reductions in photosynthetic rates of 32% for drought-tolerant and 84% for drought-susceptible genotypes; and Schapendonk *et al.* (1989) recorded the greatest reduction in photosynthetic rate as a result of water stress in a drought-sensitive cultivar. Reports in this regard are, however, not consistent: in the same trial conducted by Schapendonk *et al.* (1989), other cultivars which differ in their drought tolerance varied little in their photosynthetic response to water stress. Wilcox & Ashley (1982) have also shown that there is no consistent reduction in photosynthetic rate attributable to stress treatments among the different potato cultivars they studied. Schapendonk *et al.* (1989), therefore concluded that gas exchange measurements at a certain developmental stage can at best only explain part of the variation in drought tolerance encountered in the field.

The objective of this facet of the study was to relate photosynthetic rate and stomatal resistance of potato genotypes exposed to water stress to yield response. Field screening for drought tolerant genotypes is arguably the best method of selection, but it is tedious and expensive, and only a limited number of genotypes can be evaluated simultaneously. This has prompted a search for reliable techniques suitable for the early selection of large numbers of potentially drought-tolerant parental material. Most of the published research in this field has focussed on single or short-term measurements of photosynthetic rate at certain physiological stages. For this reason the possibility was explored of using mean seasonal photosynthetic rate and stomatal resistance in stressed and unstressed conditions as indicators of drought tolerance in potato genotypes.

6.2 Materials and methods

Information on the cultivation practices and water treatments applied during the execution of the trials is described in detail in Chapters 3 and 4. Physiological measurements were made during the 1992 autumn, 1992 spring and 1993 spring plantings.

Gas exchange measurements were made periodically throughout the growing season between 10:00 and 12:00, but only on days when the photosynthetically active radiation (PAR) was higher than 1000 μmol m^{-2} s^{-1}. Due to the fact that measurements were not necessarily made at comparable stages within each irrigation cycle, the data of different plantings could not be compared. Comparisons between genotypes within the same season were, however, justified as measurements were carried out on the same days.

An LI-6250 portable photosynthesis system (LI-COR Ltd., Lincoln, USA) with a 1000 cm^3 leaf chamber was used to carry out measurements on intact leaves. Leaf area inserts were used to limit the exposed leaf area to 8 cm^2. All measurements were on the terminal leaflet of the third to fifth expanded leaf from the top of the plant. Only sunlit leaves were used and after insertion, the leaf chamber was positioned so as to ensure continued exposure of the adaxial leaf surface to maximum sunlight. Two to three measurements per plot were made on two replications of the trial. The 15-second measurements started immediately after a constant reduction in CO_2 concentration was observed. Leaf photosynthesis, transpiration and stomatal resistance were calculated from these measurements.

During 1992, data were recorded on 17 occasions for the autumn planting, and on 18 occasions for the spring planting. Only eight observations were possible during the 1993 spring planting due to the high number of cloudy days. In the case of the early to medium maturity class cultivars, which senesce earlier, fewer measurements were possible. During the 1992 autumn planting measurements were carried out only on the W1, W3 and W5 treatments.

6.3 Results and discussion

Both photosynthetic rate (Pn) and stomatal resistance (Rs) responded to water regimes in all plantings. Genotypes showed increased stomatal resistance and decreased rates of photosynthesis because of water stress, as has frequently been reported (Rutherfoord & De Jager, 1975; Dwelle *et al.*, 1981a; Dwelle 1985; Bansal & Nagarajan, 1986; Vos & Groenwold, 1988; Ezekiel *et al.*, 1989). All the genotypes in the present study revealed similar trends over the growing period; only the photosynthetic response of Late Harvest to water stress is therefore presented graphically as an example (Figure 6.1).

A considerable degree of variation in Pn and Rs was evident for all treatments possibly due to changing weather conditions. Under non limiting conditions, leaf conductance is primarily dependent on the level of irradiation (Stark, 1987), which varies form day to day. The greater degree of variation in the case of the drier treatments could be explained by the high frequency of small irrigation quantities. In especially the dry treatments, Pn declined gradually until irrigation, whereafter it recovered rapidly, contributing to the observed variation. Stomatal resistance showed the opposite response, which is in agreement with the results of Vos & Groenwold (1989). Similar daily oscillations of stomatal conductance as a result of changing weather conditions and frequent irrigations were reported by Vos & Groenwold (1989) in their drought studies.

Short-term measurements of physiological indices reflect the plant's reaction to water stress at the moment of observation, while tuber yield is a complex and integrated function of all processes throughout the plant life cycle. Mean values of physiological measurements, especially those collected during tuber bulking, should correlate better with tuber yield than incidental measurements (Shimshi *et al.*, 1983). Differences in Pn and Rs rates of different water treatments remained relatively stable over time in the present investigation, in spite of

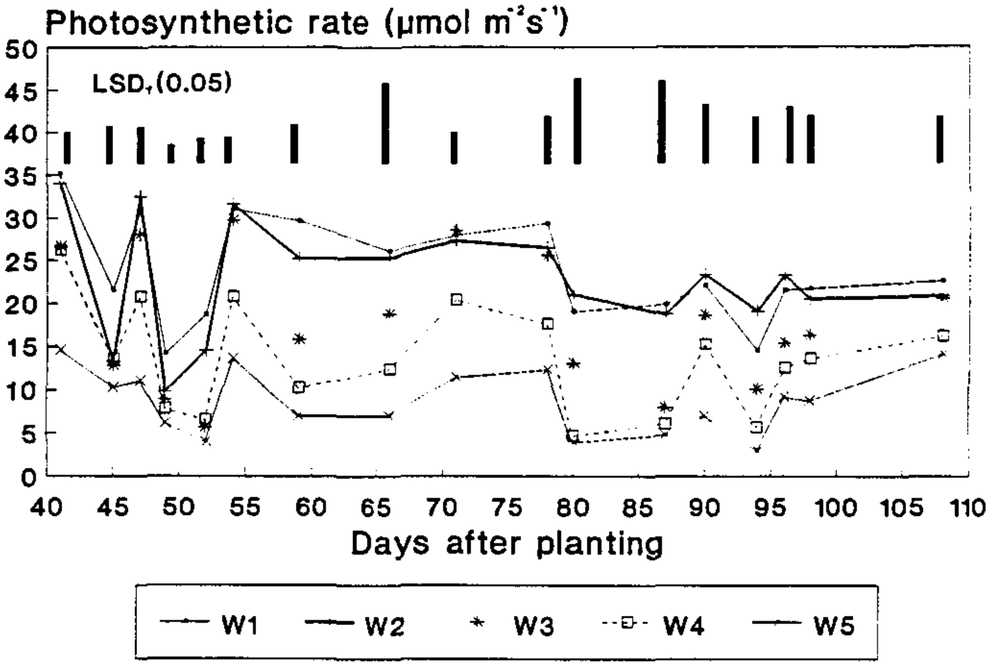


FIGURE 6.1: **Within-season variation of net photosynthetic rate of Late Harvest as influenced by five water regimes**

the observed daily variations. Therefore, seasonal mean values of photosynthetic rate and stomatal resistance for each genotype and water treatment were calculated. This method was also used by Schapendonk *et al.* (1989) and Shimshi *et al.* (1983) to enable the comparison of tuber yield with the physiological response of potato genotypes to stress.

The mean values of Pn and Rs of each genotype for the W1 treatment during the different seasons, are presented in Table 6.1. The values obtained are of the same order as those reported by Wolf (1993) for unstressed potato leaves. Fairly small genotypic differences in the average photosynthetic rate of unstressed plants were recorded in this study, although the genotypes Mnandi and 83-252-1 had lower values in spring, while Kimberley Choice and the two medium growing period cultivars had lower values in the autumn planting. This confirms that actual values of photosynthetic rate do not give any indication of the expected tuber yield, since Mnandi produced high yields for all the water treatments (Chapter 4).

TABLE 6.1 : **Mean values of photosynthetic rate and stomatal resistance recorded for the well-watered treatment (W1) of each genotype during different plantings, as well as linear regression coefficients for the correlations between Pn, Rs and tuber yield**

Genotype	Planting	Pn [1] (μmol m^{-2} s^{-1})	n [2]	SEM [3]	Regressions			Rs [4] (s cm^{-1})	n	SEM	a	b	r
					a	b	r						
Vanderplank	Autumn 1992	20.47	17	1.85	-1.393	0.836	0.916	1.064	16	0.165	44.448	-8.167	-0.935
Buffelspoort		22.81	17	1.73	-2.494	0.984	0.972	0.851	17	0.105	48.499	-6.801	-0.950
Up-to-date		18.82	17	1.64	1.088	1.065	0.999	1.355	17	0.208	57.957	-8.171	-0.999
BP1		18.74	17	2.39	-0.726	1.066	0.919	1.129	16	0.236	51.717	-6.872	-0.943
Kimberley Choice		18.80	17	2.10	0.447	0.912	0.998	1.440	16	0.244	47.83	-5.806	-0.994
Late Harvest		25.30	17	1.90	-1.284	0.760	0.991	0.775	16	0.090	45.062	-7.960	-0.976
Vanderplank	Spring 1992	20.16	16	1.37	-4.615	2.444	0.985	1.590	16		58.885	-10.279	-0.982
Up-to-date		23.73	18	1.66	-28.01	3.570	0.991	1.054	18		76.088	-19.539	-0.980
Late Harvest		23.70	18	1.38	-5.921	2.303	0.975	0.884	18		62.596	-14.582	-0.992
Late Harvest	Spring 1993	22.00	8	1.77	4.760	2.044	0.941	0.870	8	0.171	52.718	-5.724	-0.970
Hoëvelder		22.45	8	2.09	-4.413	2.903	0.971	1.065	8	0.276	68.501	-10.101	-0.984
Mnandi		17.82	8	1.41	-7.772	4.555	0.938	1.391	8	0.158	86.606	-11.809	-0.987
Up-to-date	Spring 1993	24.51	6	1.97	15.295	2.272	0.866	1.018	6	0.271	76.097	-7.128	-0.921
82-252-5		21.42	7	1.15	10.935	1.953	0.926	1.145	6	0.222	59.735	-6.732	-0.948
83-252-1		19.64	7	1.70	9.010	2.507	0.955	1.063	6	0.157	64.171	-7.195	-0.996

1 Pn = Net photosynthetic rate (μmol m^{-2}s^{-1})
2 n = number of observations
3 SEM = standard error of means
4 Rs = stomatal resistance (s cm^{-1})

Canopy size and shape may affect the relationship between photosynthetic rate and tuber yield: canopies intermediate in size and degree of upright growth habit appear to be the most efficient in terms of maximising tuber bulking rates (Lynch & Kozub, 1993). In the present study the size and shape of canopies were not recorded, but visual differences between genotypes were evident. These differences may have contributed to differences in the relationship between photosynthetic rate and tuber yield.

Regarding stomatal resistance, differences were observed in the mean Rs values recorded in the W1 treatment for the different genotypes (Table 6.1). Late Harvest (late cultivar standard) consistently had lower Rs values in the unstressed treatment (W1) than the other genotypes it was compared to in the same trial. The mean stomatal resistance of Up-to-date, the medium standard, remained fairly constant in the different trials (as was the case with Late Harvest), although it was slightly higher in autumn 1992.

Bansal & Nagarajan (1986), in an investigation of several physiological parameters as potential indices of drought resistance in potato genotypes, concluded that stomatal conductance is a better parameter than water saturation deficit and proline content. They found that the genotypes with the lowest stomatal conductance (i.e. highest resistance) for droughted treatments also showed the best drought tolerance. This does not seem to have been a consistent trend in the present trials: Late Harvest, for example, had the lowest stomatal resistance (or highest conductance) for the W5 treatment in the autumn 1992 trial (data not shown), but also appeared to be one of the more drought tolerant genotypes evaluated (Chapter 9). However, the severity of the drought stress imposed by Bansal & Nagarajan (1986) is questionable, as some genotypes in their study yielded almost 50% higher at the stressed treatment, compared to the unstressed treatment.

Linear regression was used to correlate seasonal mean photosynthetic rates and stomatal resistances of genotypes with their marketable yields (Table 6.1). Good correlations (r-values) were obtained for both parameters from all genotypes. These findings differ from those of Dwelle *et al.* (1981), who reported poor correlations between these parameters and tuber yield. The use of short-term measurements may be the reason for the poor correlations recorded in their study.

From Table 6.1 it is noteworthy that the slopes of regression between mean photosynthetic rate and tuber yield were always lower for Late Harvest than for the other genotypes in the same trial. This suggests that for Late Harvest tuber yield was less sensitive to reductions in photosynthetic rate than the other genotypes, which might be an indication of drought tolerance. However, this relation was not consistent for all genotypes: the calculated slopes of regression for Up-to-date, a drought sensitive genotype, were sometimes lower than those of more drought tolerant genotypes such as 83-252-1.

It is clear from these experiments that external factors other than water supply influence the relationship between mean photosynthetic rate, stomatal resistance and tuber yield, as both the intercepts and slopes of the regression functions changed with seasons. According to Dwelle (1985), characteristics such as canopy size and the distribution of assimilates may change as a result of factors such as temperature, thereby altering tuber yield. Jefferies & MacKerron (1993) have also demonstrated that the harvest index (distribution of assimilates) of some genotypes was reduced as a consequence of drought: Up-to-date, for instance, showed the greatest reduction in yield and had the lowest harvest index in the drought-stressed treatments. Decreased leaf expansion rates at temperatures above 25 °C, resulting in reduced leaf area indices, were observed by Bhagsari, Webb, Phatak & Jaworski (1988). They further observed that the availability of photosynthate for tuber development was reduced because canopy respiration rates increased two to three fold when temperatures rose from 25 °C to 35 °C.

From the preceding discussion it therefore appears that actual measurements of photosynthetic rate and stomatal resistance have little potential as aids in estimating tuber yield as affected by water supply, as their relationship to tuber yield is unique for each genotype and season, as well as for timing of measurements. As an alternative, the rates of reduction in photosynthesis and stomatal conductance in response to drought have previously been investigated as potential screening methods for drought tolerance in potatoes (Schapendonk *et al.*, 1989; Sukumaran *et al.*, 1989; Vos & Groenwold, 1989). These authors expressed the rates of photosynthesis and stomatal conductance recorded in water-stressed treatments relative to their values in an unstressed control. They concluded that genotypes that show greater reduction in rates of photosynthesis and stomatal conductance due to drought, are probably more drought sensitive.

The mean photosynthetic rates and stomatal resistances recorded for each genotype and water treatment in the present study are expressed relative to their values for the W1 treatment in Table 6.2. For the W2 treatment almost no decline in photosynthetic rate was observed for most of the genotypes (as was observed for tuber yield). For the other treatments (W3 - W5), marked reductions in photosynthetic rate and increase in stomatal resistance were observed for all genotypes.

Reductions in photosynthetic rate can generally be related to reductions in tuber yield, especially for the W3 and W4 treatments. Up-to-date is, however, an exception: during the spring plantings its yields generally declined more rapidly than its photosynthetic rate. The sensitivity of this genotype to high temperatures (Wolf *et al.*, 1989) probably aggravated the detrimental effects of water stress on its yield in spring. In a study by Leskovar *et al.* (1989) under similar conditions, it was found that despite Up-to-date's capacity to avoid short periods of water stress, it produced lower tuber yields than the other genotypes as a result of its sensitivity to high temperatures. High temperatures enhanced top growth at the expense of tuber growth in this cultivar. For some unknown reason, in the 1993 spring planting relative photosynthetic rates recorded for all genotypes in the W4 treatment of rain shelter #2 correlated poorly with relative yields.

Regression analysis on the data recorded for the W3, W4 and W5 treatments of all genotypes in all plantings indicates that relative photosynthetic rates are linearly related to relative tuber yields, as described by the following equation:

$$\textbf{Relative yield} = \textbf{0.0902 (SE 0.1551)} + \textbf{0.7696 (SE 0.1075) x relative Pn} \quad (r=0.758) \tag{6.1}$$

The exclusion of the Up-to-date data, and the data of the 1993 planting mentioned above,

TABLE 6.2 : **Mean relative (expressed as fractions of values of the W1 treatment) photosynthetic rates, stomatal resistances and tuber yields, *recorded for each genotype for five different water treatments***

Genotype	Planting	W2			W3			W4			W5		
		Pn[1]	Rs[2]	Yield	Pn	Rs	Yield	Pn	Rs	Yield	Pn	Rs	Yield
Vanderplank	Autumn				1.017	1.086	0.722				0.380	3.845	0.273
Buffelspoort	1992				0.882	1.505	0.697				0.314	6.582	0.227
Up-to-date					0.761	1.940	0.792				0.308	3.780	0.342
BP1					0.973	1.417	0.711				0.392	4.677	0.328
Kimberley Choice					0.718	2.424	0.762				0.268	4.340	0.281
Late Harvest					0.747	2.390	0.655				0.373	5.240	0.339
Vanderplank	Spring	0.981	1.011	0.894	0.647	1.656	0.677	0.533	2.175	0.425	0.286	3.190	0.196
Up-to-date	1992	0.970	1.011	1.111	0.722	1.928	0.617	0.544	2.735	0.287	0.348	3.711	0.063
Late Harvest		1.002	1.350	0.983	0.751	2.030	0.808	0.559	2.576	0.591	0.360	4.070	0.207
Late Harvest	Spring	0.995	1.062	0.803	0.591	3.525	0.703	0.420	4.572	0.503	0.205	9.000	0.166
Hoëvelder	1993	0.980	0.949	0.858	0.615	2.510	0.598	0.401	3.918	0.441	0.267	5.741	0.107
Mnandi		0.828	1.609	0.975	0.561	2.578	0.712	0.505	2.982	0.521	0.351	4.521	0.181
Up-to-date	Spring	0.927	0.647	1.021	0.230	6.064	0.760	0.180	7.115	0.282	0.118	8.250	0.115
82-252-5	1993	0.975	0.882	0.870	0.507	3.519	0.637	0.189	5.099	0.486	0.188	5.640	0.165
83-252-1		0.921	1.260	0.895	0.413	3.847	0.628	0.251	5.098	0.427	0.187	7.007	0.174

[1] Pn = relative net photosynthetic rate

[2] Rs = relative stomatal resistance

improve the correlation coefficient substantially, and the regression function changes to the following:

$$\textbf{Relative yield} = 0.0309\ (\text{SE } 0.1124) + 0.8752\ (\text{SE } 0.0853) \times \text{relative } Pn \quad (r=0.879) \tag{6.2}$$

The linear relationship between relative photosynthetic rate and relative tuber yield indicates that for most of the genotypes evaluated in this trial, yield reduction as a result of drought might be predicted by a simple model (Equation 6.2) if the reduction in photosynthetic rate as a result of drought is known.

Good correlation coefficients were obtained for the linear relationship between relative stomatal resistance and relative tuber yield, but they were lower than the correlation coefficients obtained for photosynthetic rate. The following linear regression function for the data from the W3, W4 and W5 treatments of all genotypes represents the relationship between relative stomatal resistance and relative tuber yield:

$$\textbf{Relative yield} = 0.7552\ (\text{SE } 0.1839) - 0.0781\ (\text{SE } 0.0178) \times \text{relative } Rs \quad (r=-0.638) \tag{6.3}$$

Exclusion of the Up-to-date spring data, and the data for the 1993 spring planting, improves the regression coefficient and changes the regression function to:

$$\textbf{Relative yield} = 0.8328\ (\text{SE } 0.1378) - 0.1013\ (\text{SE } 0.0150) \times \text{relative } Rs \quad (r=-0.821) \tag{6.4}$$

The relationship between tuber yield reduction and increased stomatal resistance appears to be similar for all genotypes, as is the case with photosynthetic rate. This indicates that if the increase in stomatal resistance due to water stress is known, the expected yield reduction might be estimated with the aid of a simple regression model (Equation 6.4).

The effect of high temperatures on the distribution of assimilates is not accounted for by these models. A heat-sensitive genotype may therefore produce lower tuber yields than predicted from its relative stomatal resistance or photosynthetic rate. Obviously, numerous processes are involved in the adaptation to drought, and simple direct relationships between drought tolerance and ultimate tuber yield can not be established.

6.4 Conclusions

Photosynthetic rate (Pn) and stomatal resistance (Rs) are potentially useful predictors of drought tolerance in potato genotypes, since the relationship between relative values of these indices and relative tuber yields appears to be consistent. Actual measurements of either of these parameters are not useful for estimating tuber yield, although correlations with tuber yield were good. This is attributable to the fact that the relationship between Pn or Rs and tuber yield is affected by factors (e.g. temperature) which may influence aspects such as canopy development and harvest index.

Simple regression models are suggested for the estimation of expected reductions in tuber yield from the reductions in measured rates of Pn or Rs resulting from drought stress. Although these empirical models did not account for actual yield reductions under all circumstances, they still appear to be useful for selection of drought tolerance: all genotypes which showed great reductions in photosynthetic rate (or increases in stomatal resistance) as a result of drought, were prone to yield reduction in the current study. The limited number of genotypes for which these physiological measurements were recorded, did not differ substantially in their ability to tolerate drought (see Chapter 9), except for the cultivar Up-to-date, which is drought (and heat) sensitive. Consequently, large differences in relative photosynthetic rates, stomatal resistances and tuber yields were not obvious.

In conclusion, the use of relative photosynthetic rate and stomatal resistance as indices of drought tolerance in potato genotypes is promising, but further investigation on a wider range of more diverse genotypes is needed.

CHAPTER 7

THE EFFECT OF WATER REGIMES ON WATER-USE CHARACTERISTICS OF POTATO GENOTYPES

7.1 Introduction

Potatoes require a relatively high level of soil water for optimum yield and quality (Miller & Martin, 1987b). The sensitivity of the crop to even short periods of mild water stress has been demonstrated in many research projects (Van Loon, 1981; Dwelle, 1985; Van Loon, 1986). The effects of water stress on tuber yield and quality depend on the timing and severity of the stress. Tuber number is limited by water stress during the tuber initiation phase, while the rate of tuber growth is reduced by water stress in the bulking phase. Total yield is thus primarily harmed by drought between tuber initiation and maturity (Miller & Martin, 1987b). Interruption in water supply may influence tuber quality at almost any growth stage after tuber initiation (Mould & Rutherfoord, 1980; Ojala *et al.*, 1990; Jefferies & MacKerron, 1993; Shock *et al.*, 1993).

Most published water-use data for potato crops have been recorded in temperate climates (Doorenbos & Kassam, 1979). In tropical and subtropical climates the high evaporative demand increases crop water requirements, which may compound the sensitivity to water stress, resulting in greater yield reductions than those expected from similar water deficits under cooler conditions (Trebejo & Midmore, 1990). According to Doorenbos & Kassam (1979), the seasonal water requirement of potato crops varies between 500 and 700 mm and water-use efficiencies range between 40 and 70 kg ha^{-1} mm^{-1} for a 120- to 150-day crop, depending on the season. In the subtropical climate of Peru, Trebejo & Midmore (1990) recorded mean water-use efficiencies of 39 kg ha^{-1} mm^{-1} and 124 kg ha^{-1} mm^{-1} for hot and cool seasons, respectively. They recorded higher yield losses and lower water-use efficiencies in hot seasons, mainly because of the greater saturation vapour pressure deficit in hot seasons.

Droughted plots showed the highest water-use efficiencies due to greater harvest index values and more efficient interception of solar radiation per unit water applied. Lower harvest indices in summer were to some extent responsible for seasonal differences in water-use efficiencies.

Little is known about the water requirements of potatoes in the southern African subtropical climate. The water requirements of potato crops do presumably also depend on the season, as potatoes may be cultivated at different times of the year for some localities. The yield response of different potato genotypes was discussed in Chapter 4. In this chapter the specific water requirements of locally cultivated genotypes in different environments will be investigated.

7.2 Materials and methods

Studies to determine the water requirements and the effects of different levels of water stress on the production of different potato genotypes were carried out over a period of four years. The details of cultivation practices and treatments applied in the three spring and four autumn plantings are fully described in Chapters 2 and 3.

An irrigation boom system was used to induce five levels of water stress. Soil-water content of all the plots was determined three times per week at 150-mm intervals to a depth of 1200 mm using a neutron probe (DR 503). On some occasions the measuring depth was only down to 600 mm. The irrigation amount was calculated according to the soil-water deficit in the 0 - 600-mm zone. Irrigation scheduling was based on the soil-water content of the W1 treatment and the profile was refilled by irrigation whenever there was a 20% depletion of the total amount of water held by the root zone at field capacity. The other four treatments were irrigated on the same day, but on average received 82, 56, 46 and 28 percent, respectively of the amount applied to W1. The soil-water deficit was calculated as follows for each of the 300-mm zones:

$$D_i = (FC_i - WC_i) \times \rho b_i \times d_i \qquad (7.1)$$

where D_i = soil-water deficit (mm) in soil layer i, FC_i = gravimetric field capacity (%) of soil layer i, WC_i = gravimetric soil-water content (%) of soil layer i, b_i = bulk density (g cm^{-3}) of soil layer i, and d_i = depth of soil layer i (m). The change in soil-water content (dW) between two measurement dates was calculated as:

$$\mathbf{dW = D_0 - D_i} \tag{7.2}$$

where D_0 and D_i = soil-water deficits on days 0 and i, respectively. The evapo-transpiration (ET) was calculated as:

$$\mathbf{ET = dW + I} \tag{7.3}$$

where I = amount of irrigation (mm), assuming that run-off and drainage were zero. Total water use (WU) at the end of the season was calculated as:

$$\mathbf{WU = D_E - D_0 + I} \tag{7.4}$$

where D_E and D_0 are the soil-water deficits at the end and start of the growing season, respectively.

Tuber yield and tuber-size distribution results are reported and discussed in Chapter 4. In this chapter the total amounts of water used by the various genotypes for the different water treatments are presented. Water-use efficiencies and production functions of the different genotypes are also discussed.

7.3 Results and discussion

The total amount of water used by the different genotypes subjected to the wet treatments (W1) ranged from 215 mm in the 1995 autumn to 820 mm in the 1994 spring planting (Tables 7.1 and 7.2).

TABLE 7.1 : Total Class A-pan evaporation and water use (mm) of potato genotypes exposed to five water treatments during spring plantings

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water use (mm) per water treatment				
				W1	W2	W3	W4	W5
Spring 1992	Vanderplank	1	1046	453	409	331	273	240
	Up-to-date	1		545	493	406	326	275
	Late Harvest	1		554	495	405	328	269
	Vanderplank	2		663	580	499	377	299
	Up-to-date	2		708	675	574	427	326
	Late Harvest	2		709	672	585	426	335
Spring 1993	Late Harvest	1	947	654	531	395	338	235
	Hoëvelder	1		655	535	397	334	222
	Mnandi	1		650	516	382	328	226
	Up-to-date	2		613	530	409	344	254
	82-252-5	2		616	529	413	347	242
	83-252-1	2		621	504	396	349	252
Spring 1994	Late Harvest	1	1070	817	627	463	384	285
	81-163-40	1		820	631	469	385	293
	83-363-67	1		799	611	459	388	266
	Up-to-date	2		813	652	492	405	259
	Mondial	2		806	657	477	377	271
	84-304-4	2		340	252	217	182	139

TABLE 7.2 : **Total Class A-pan evaporation and water use (mm) of potato genotypes exposed to five water treatments during autumn plantings**

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water use (mm) per water treatment				
				W1	W2	W3	W4	W5
Autumn 1992	Vanderplank	1 & 2	612	346	207	192	175	116
	Buffelspoort	1 & 2		344	287	201	174	115
	Up-to-date	1 & 2		344	273	191	169	110
	BP1	1 & 2		354	276	204	175	122
	Kimberley Choice	1 & 2		358	292	198	174	130
	Late Harvest	1 & 2		355	279	210	171	125
Autumn 1993	Vanderplank	1	528	277	256	208	170	137
	Up-to-date	1		282	261	211	171	136
	Late Harvest	1		274	254	201	164	131
	Vanderplank	2		494	441	352	281	228
	Up-to-date	2		495	445	362	288	236
	Late Harvest	2		492	439	356	283	230
Autumn 1994	Late Harvest	1	562	554	390	296	233	174
	Hoëvelder	1		558	391	303	235	179
	Mnandi	1		589	400	296	233	170
	Up-to-date	2		577	436	312	270	205
	82-252-5	2		557	437	323	293	199
	83-252-1	2		554	436	306	280	188
Autumn 1995	Late Harvest	1	478	222	206	174	168	148
	81-163-40	1		217	202	174	166	141
	83-363-67	1		215	200	179	168	149
	Up-to-date	2		282	234	187	170	145
	Mondial	2		265	228	192	186	147
	84-304-4	2		219	202	145	131	94

Genotypes showed small differences in total seasonal water use within the same trial and for the same water treatment. Vanderplank, an early cultivar, used less water than the other genotypes in the same trial during spring. The genotype 84-304-4 used the least water in both spring and autumn plantings, because of *Erwinia* disease (spring 1994) and plant population problems (autumn 1995) encountered. Total water use was a function of the amount of water applied, and genotypes of the same maturity class used approximately the same amount of water. Throughout the study there was little evidence of genotypes tending to deplete the soil water at different rates (see Figures 7.1 and 7.2 as examples). As genotypes in the same trial received the same amount of water, differences in water use can only be explained by differences in initial soil-water content and by the degree of soil-water depletion at the end of the season (equation 7.4). Deep percolation (not accounted for) might also have occurred for some of the genotypes since the mean deficit of the W1 regime of all genotypes was used to calculate irrigation amounts. It therefore seems that, although the irrigation boom method is suitable for drought-screening purposes, application of the same amounts of water to all genotypes and the limited number of water regimes offered, may be of the biggest disadvantages of the irrigation boom in determining the water requirements of crops.

The reason for lower water use of the same genotypes in rain shelter #1, compared to rain shelter #2 for the 1993 autumn planting is not clear. The lower total water use and total yields obtained in the wet treatment of rain shelter #1 may indicate that the plants were exposed to water stress, probably due to incorrect irrigation scheduling.

As the level of soil-water depletion from the different soil layers showed similar seasonal trends, the graphs of only one season are presented as examples (Figures 7.1 to 7.4). No significant genotypic differences were evident in any of the soil layers: the soil zones of highest root activity, the shallower zones, showed the highest degree of depletion with only a small portion of the total water used from soil layers below 900 mm.

Water use of the same genotypes in spring plantings was between 12 % (spring 1993 versus autumn 1994) and 210% (spring 1994 versus autumn 1995) higher than in autumn. This is partly attributable to the shorter autumn season, but also to the high atmospheric evaporative

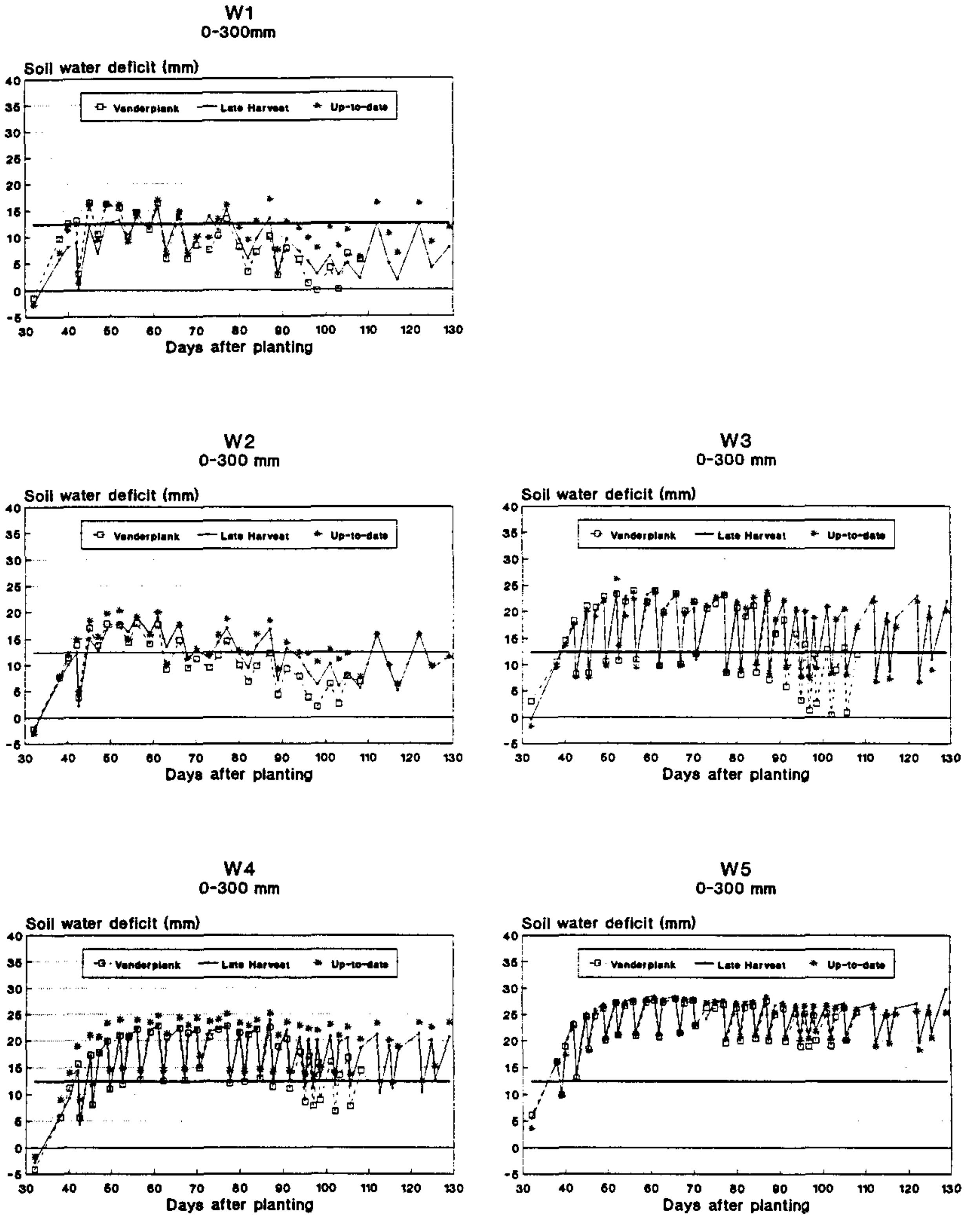


FIGURE 7.1 : Seasonal variation of soil-water deficits in the 0 to 300-mm soil zone for three genotypes at five water treatments (W1 - W5). Solid horizontal line represents 20% depletion of total soil water

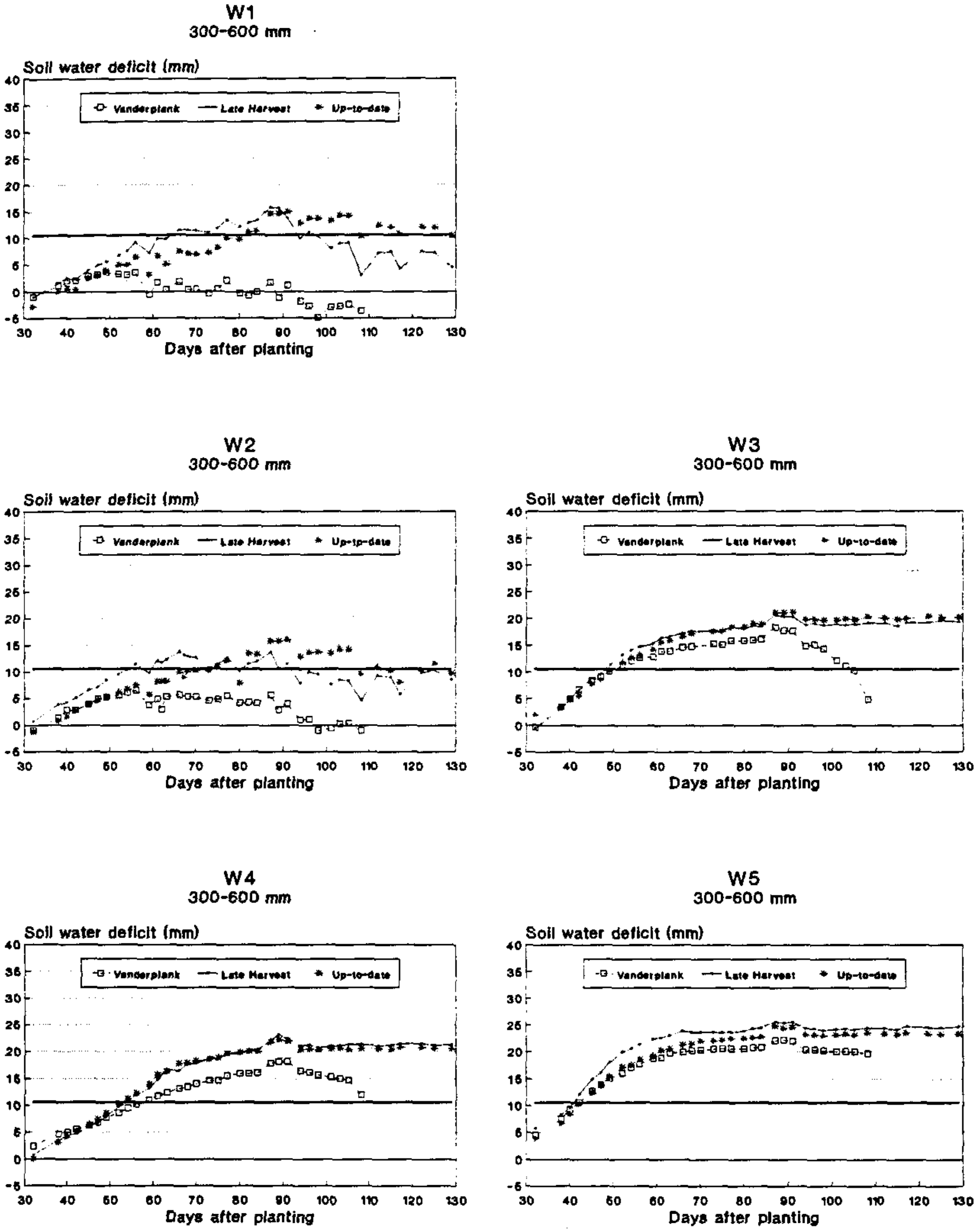


FIGURE 7.2 : Seasonal variation of soil-water deficits in the 300 to 600-mm soil zone for three genotypes at five water treatments (W1 - W5). Solid horizontal line represents 20% depletion of total soil water

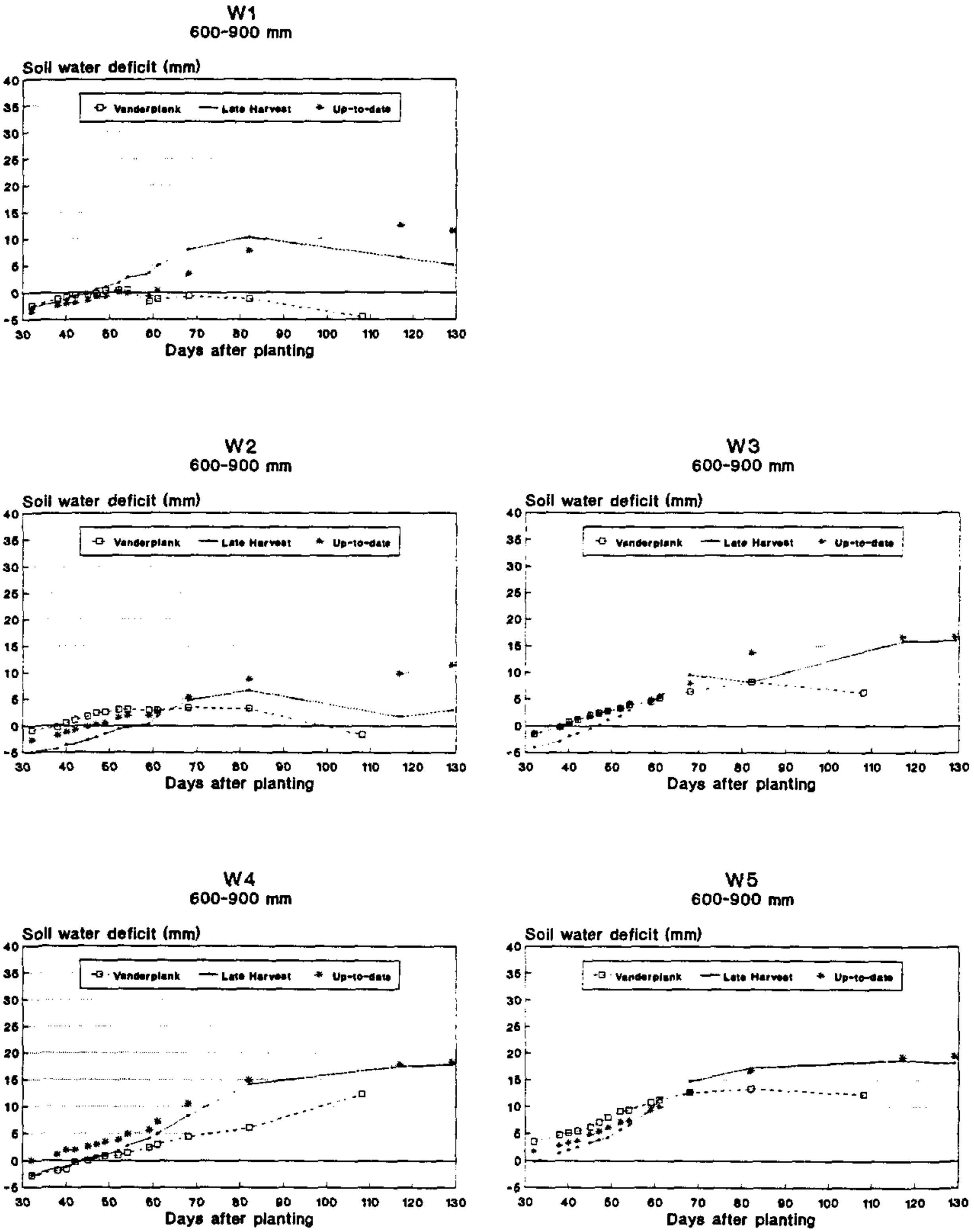


FIGURE 7.3 : Seasonal variation of soil-water deficits in the 600 to 900-mm soil zone for three genotypes at five water treatments (W1 - W5)

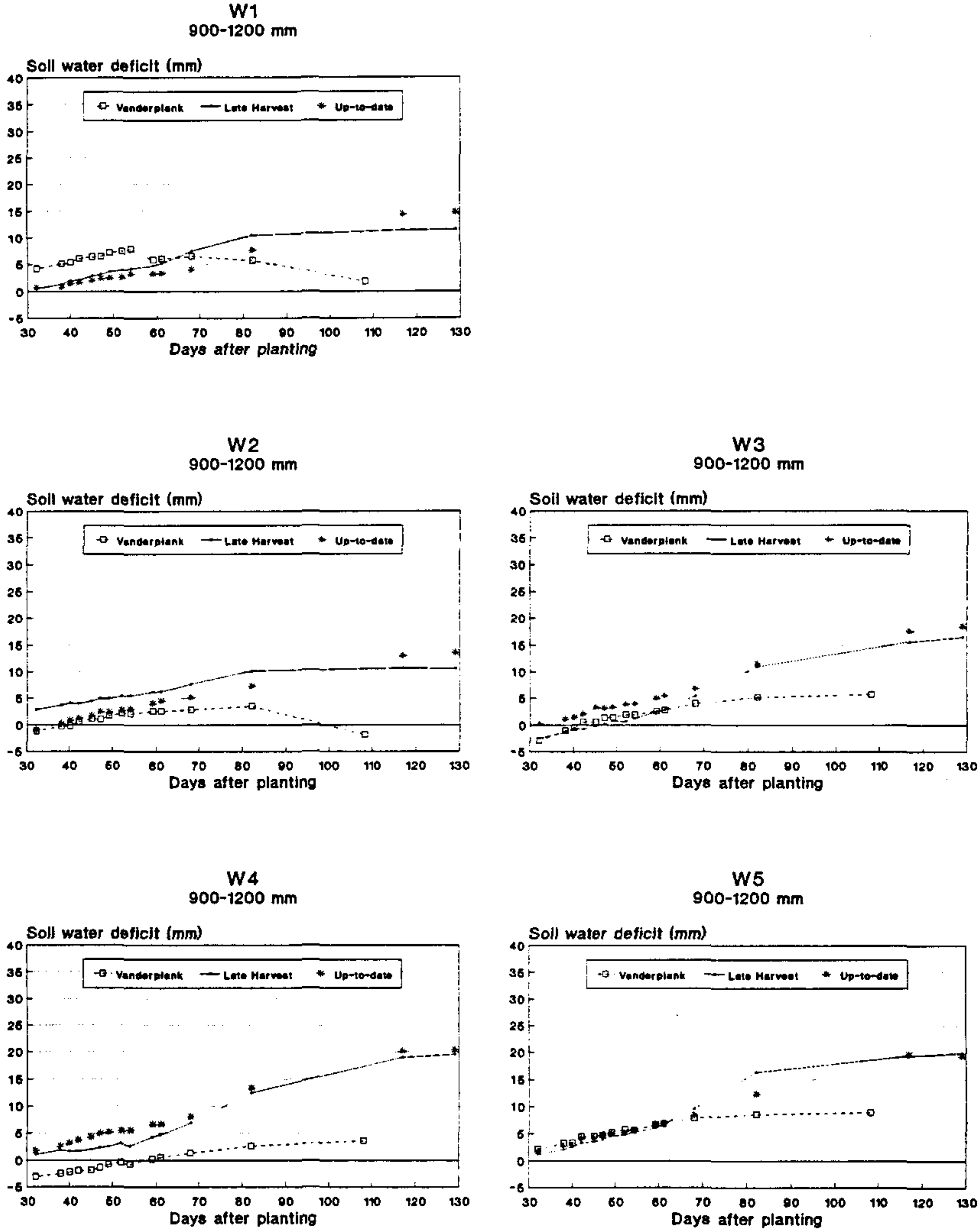


FIGURE 7.4 : Seasonal variation of soil-water deficits in the 900 to 1200-mm soil zone for three genotypes at five water treatments (W1 - W5)

demand in the spring plantings (see Tables 7.1 & 7.2 and Figure 3.1). Tanner (1981) suggested the normalising of transpiration (T) for seasonal vapour pressure deficit (e*- e) to make transpiration data of different seasons more comparable. For a given crop the following relationship then becomes true:

$$Y/T \quad = k \,/\, (e^{*} - e) \tag{7.5}$$

or

$$Y/k \quad = T \,/\, (e^{*} - e) \tag{7.6}$$

where Y is the total dry matter produced in mass per area; T is the seasonal transpiration; k is constant for a specific crop and canopy; and (e*- e) is the daytime saturation vapour pressure deficit of the air, assuming that leaf temperature is equal to air temperature.

Normalised seasonal values of T/(e*- e) can be calculated in various ways. The best method is to derive an integrated value for the growing period from accumulated values of daily normalised evapotranspiration measured with a lysimeter. A second method, which usually gives an underestimate of k (Tanner, 1981), is to divide the mean seasonal transpiration by the mean seasonal daytime vapour pressure deficit.

The value of daily normalised transpiration will depend on how (e*- e) is calculated. Using an integral for the daytime transpiration period, i.e. the mean of hourly (e*- e) for the transpiration period, gives the best estimate of daily (e*- e). When hourly data is not available, daily normalised transpiration can be calculated using the mean of (e*- e) at minimum and maximum temperatures.

As it was not possible in this study to measure transpiration separately, evapotranspiration data (total water use) were normalised. Since complete weather data sets were available only for the period autumn 1993 to autumn 1995, the water-use data prior to that could not be normalised. Daily (e*- e) was calculated as the mean of (e*- e) at minimum and maximum temperatures, as some of the data sets lacked hourly temperatures. Normalised seasonal evapotranspiration values for the W1 treatments of the autumn 1993 to autumn 1995 plantings were used in the calculation of water-use efficiencies normalised for vapour pressure deficit.

Water-use efficiencies obtained for the different plantings are shown in Tables 7.3 and 7.4. Generally, water-use efficiencies were higher in autumn (mean 127 kg ha^{-1} mm^{-1}) than in spring plantings (mean 94 kg ha^{-1} mm^{-1}) for most of the genotypes. This trend is in agreement with those reported for other studies conducted in subtropical climates (Trebejo & Midmore, 1990). The lower water-use efficiencies recorded in summer are most probably due to greater soil evaporation and lower transpirational water-use efficiencies. Mean water-use efficiencies calculated for autumn plantings in the W1 treatments over all the years and genotypes were much higher than those recorded by Trebejo & Midmore (1990) for the same time of year (their summer trials): 127 kg ha^{-1} mm^{-1} water applied on fresh tuber mass basis versus 44.3 kg ha^{-1} mm^{-1} recorded for their unstressed treatments. The water-use efficiencies recorded by them in winter were similar to those recorded in this study in autumn: 122 kg ha^{-1} mm^{-1} versus 127 kg ha^{-1} mm^{-1}. The lower water-use efficiencies recorded by Trebejo & Midmore (1990) in summer are possibly due to the higher temperatures and higher atmospheric evaporative demand recorded for their locality.

Highest water-use efficiencies were in most instances recorded for the intermediate water regimes: in spring plantings the highest water-use efficiency values were recorded for the W2 and W3 treatments for all the genotypes, with the exception of Vanderplank during the 1992 spring planting, when the highest value was recorded for W4. In the autumn plantings most of the highest water-use efficiencies were also recorded in W2 and W3, but in 1993 and 1994 the highest water-use efficiencies were recorded in W4 for some of the genotypes. The highest water-use efficiencies were recorded at the W1 treatment for some genotypes during the cool 1995 autumn.

It was difficult to compare genotypic water-use efficiencies over different years because of year effects. Genotypes were therefore evaluated according to their water-use efficiencies within the same maturity class and season. During the 1992 spring planting either Late

TABLE 7.3: **Water-use efficiencies (kg ha^{-1} mm $^{-1}$) of potato genotypes exposed to five water treatments during spring plantings**

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water use (mm)				
				W1	W2	W3	W4	W5
Spring 1992	Vanderplank	1	1046	107.7	108.9	102.3	78.0	47.9
	Up-to-date	1		89.4	96.7	97.7	89.1	40.8
	Late Harvest	1		100.0	102.3	104.4	55.0	17.1
	Vanderplank	2		73.3	80.0	88.2	91.7	59.0
	Up-to-date	2		79.5	81.8	81.2	76.9	41.1
	Late Harvest	2		91.4	99.7	95.3	73.1	32.9
Spring 1993	Late Harvest	1	947	86.2	85.4	104.2	91.3	57.0
	Hoëvelder	1		101.4	110.2	109.8	96.4	49.7
	Mnandi	1		110.6	132.5	135.4	122.1	74.1
	Up-to-date	2		116.8	140.6	140.0	63.4	45.4
	82-252-5	2		93.9	99.0	94.6	88.5	49.5
	83-252-1	2		98.1	108.3	98.1	81.4	52.7
Spring 1994	Late Harvest	1	1070	64.4	86.0	102.4	99.7	59.7
	81-163-40	1		73.8	82.7	106.8	86.2	16.7
	83-363-67	1		81.4	102.0	109.2	99.2	49.2
	Up-to-date	2		99.4	103.8	100.2	82.4	41.3
	Mondial	2		90.5	100.4	97.6	70.6	37.6
	84-304-4	2		136.3	160.9	162.4	120.1	67.3

TABLE 7.4 : Water-use efficiencies (kg ha^{-1} mm^{-1}) of potato genotypes exposed to five water treatments during autumn plantings

Planting	Genotype	Rain shelter #	A-pan evaporation (mm)	Water-use efficiencies (kg ha^{-1} mm^{-1})				
				W1	W2	W3	W4	W5
Autumn 1992	Vanderplank	1 & 2	612	118.6	206.8	156.3	117.1	96.6
	Buffelspoort	1 & 2		140.4	161.8	167.4	123.9	95.8
	Up-to-date	1 & 2		135.0	171.0	193.2	160.4	145.1
	BP1	1 & 2		138.7	179.8	171.1	163.2	131.9
	Kimberley Choice	1 & 2		107.4	126.3	148.0	112.0	83.3
	Late Harvest	1 & 2		115.9	139.5	128.4	131.8	111.5
Autumn 1993	Vanderplank	1	528	150.3	159.5	117.1	105.3	37.8
	Up-to-date	1		198.2	206.7	221.6	212.1	156.1
	Late Harvest	1		206.6	206.0	217.8	218.3	163.3
	Vanderplank	2		62.2	69.0	92.5	102.7	93.2
	Up-to-date	2		105.9	112.9	127.2	122.4	115.1
	Late Harvest	2		121.1	133.4	136.7	146.5	134.7
Autumn 1994	Late Harvest	1	562	105.2	121.9	146.1	125.7	114.9
	Hoëvelder	1		104.2	119.2	127.1	120.9	110.3
	Mnandi	1		115.8	128.2	149.6	134.6	113.1
	Up-to-date	2		92.9	110.6	151.8	160.2	144.3
	82-252-5	2		97.3	114.6	168.9	159.0	137.3
	83-252-1	2		87.9	103.1	153.1	159.0	129.3
Autumn 1995	Late Harvest	1	478	144.7	134.1	129.5	125.4	120.7
	81-163-40	1		180.4	154.5	160.1	148.7	144.3
	83-363-67	1		146.1	128.5	125.0	124.7	93.4
	Up-to-date	2		104.6	108.3	108.8	106.6	127.6
	Mondial	2		161.9	168.3	158.4	136.5	149.0
	84-304-4	2		115.5	126.5	139.5	127.5	151.7

TABLE 7.5 : Water-use efficiencies of potato genotypes normalised for seasonal vapour pressure dificit (kg ha^{-1} mm $^{-1}$ kPa^{-1}) for the W1 regime during spring and autumn plantings

Genotype	Rain shelter #	A-pan evaporation (mm) in spring	A-pan evaporation (mm) in autumn	Normalised water use efficiency	
				Spring	Autumn
Vanderplank	1	1046	528		161.6
Up-to-date	1				213.2
Late Harvest	1				222.2
Vanderplank	2				66.9
Up-to-date	2				113.9
Late Harvest	2				130.1
Late Harvest	1	947	562	101.8	120.9
Hoëvelder	1			119.8	119.8
Mnandi	1			130.6	133.0
Up-to-date	2			137.9	106.8
82-252-5	2			110.9	112.5
83-252-1	2			115.9	101.0
Late Harvest	1	1070	478	88.4	124.0
81-163-40	1			101.3	154.6
83-363-67	1			111.7	125.2
Up-to-date	2			136.4	89.6
Mondial	2			124.2	138.7
84-304-4	2			187.1	99.0

Harvest or Vanderplank had the best water-use efficiencies for all the water regimes with Vanderplank doing especially well under dry conditions (W4 and W5). Mnandi had the highest water-use efficiency among the late genotypes for all water treatments during the 1994 spring planting, while Up-to-date performed best only in the wetter (W1 - W3) treatments. Among the late genotypes, 83-363-67 had the highest water-use efficiencies for all regimes (except W5) during 1994. If genotype 84-304-4 is excluded from the data (because of its early death resulting from *Erwinia* disease), Up-to-date was the medium genotype with the highest water-use efficiencies in the 1994 spring planting.

During the autumn plantings there was little change in the ranking of genotypes over water treatments within the same year: in the 1992 planting BP1 and Up-to-date had the highest water-use efficiencies throughout all treatments, while in 1993 Late Harvest had the highest water-use efficiency, followed by Up-to-date. Mnandi had the highest water-use efficiencies during both the 1993 spring and 1994 autumn plantings. The genotype 82-252-5 was the medium grower with the highest water-use efficiency during the 1994 autumn. Mondial and 81-163-40 had the highest water-use efficiencies in all water treatments during 1995.

Since the assumption that air and leaf temperatures are equal is not valid for stressed plants, where leaf temperatures are sometimes higher than air temperatures, water-use data were normalised for the unstressed W1 treatments only. When normalised water-use data are used in the calculation of water-use efficiency, the water-use efficiency values for the same genotypes in different years are closer to each other: normalised water-use efficiencies for Late Harvest in the different autumn seasons were 130.1, 120.9 and 124 kg ha^{-1} mm^{-1} kPa^{-1} respectively, compared to values of 150.3, 105.2 and 144.7 kg ha^{-1} mm^{-1} before normalising (Tables 7.3 to 7.5). Some variation was, however, still evident. Firstly, in the autumn of 1993, the water-use efficiencies of rain shelter #1 were very high compared to rain shelter #2. The substantially lower yields recorded for the W1 treatment of rain shelter #1 do, however, suggest that these plants were probably stressed in the specific season, as discussed earlier in this section. Secondly, water-use efficiencies for the same genotypes were higher in autumn than spring plantings, probably due to the difference in length between the two growing seasons: spring (summer) seasons are approximately 120 to 130 days long, while autumn seasons are 75 to 80 days in length. The use of evapotranspiration instead of transpiration (as suggested by Tanner, 1981) in the calculation of water-use efficiency may be a further source for the differences encountered between seasons: in spring plantings more water is lost through evaporation without contributing to dry matter production compared to autumn.

7.4 Conclusions

The total water use of the different genotypes was similar for the same trial, possibly because water use is calculated primarily as a function of the amount of water applied. Since genotypes of the same maturity class receive the same amount of water, differences in water use can only be due to differences in initial and final soil-water contents. These differences in soil-water content were generally small, leading to small genotypic differences in calculated total water use. It is not known whether the calculated water use of genotypes would have been different if they were irrigated individually. If their water requirements would differ, the objective of this study to determine the water requirements of different genotypes may therefore not be achieved and it should be concluded that the irrigation boom method may therefore not be ideal for determining crop-water requirements of a mixture of genotypes or species, although it is useful for drought tolerance screenings.

The results obtained from this study thus provide no evidence that genotypes of the same maturity class have different water requirements and it is therefore assumed that the same crop parameters would apply for all genotypes in an irrigation scheduling model (Chapter 10).

Generally, little water was depleted below the 900- mm soil layer, regardless of genotype and water regime applied. Taking into account the small fraction of the total water use depleted below 600 mm, it is suggested that this depth be considered the maximum rooting depth for irrigation scheduling calculations. Further, the rate of depletion from the different soil layers did not differ for any of the genotypes within the same season.

The highest water-use efficiencies were, with few exceptions, recorded for the intermediate water treatments (W2 - W3). These regimes also offered the best compromise between highest yield and tuber quality, and are therefore recommended as the most beneficial. Water-use efficiencies were higher in autumn than in spring plantings, probably due to larger vapour pressure deficits and a greater evaporation component during spring, leading to more water being lost without contributing to the production of dry matter. Therefore, in production areas that offer the possibility of two planting seasons, potatoes should preferably be cultivated in autumn to ensure the highest yield per unit water applied if irrigation water is limited.

In spring plantings, the genotypes classified as drought-tolerant in Chapter 9 (Late Harvest, Mnandi, 83-363-67 and Vanderplank) generally had the highest water-use efficiencies. In some plantings, Up-to-date had the highest water-use efficiencies among the medium genotypes, but this was usually only the case for the wetter treatments (W1 - W2).

The same genotypes had the highest water-use efficiencies in all water regimes for the same trial during autumn: Late Harvest, Mnandi and 81-163-40 among the late-maturity class and BP1, Up-to-date, Mondial and 82-252-5 among the medium maturity class.

Water-use efficiencies calculated from seasonal water use, normalised for vapour pressure deficit, were similar for the same genotype and planting (spring or autumn) over different years. The differences still evident between plantings could probably be reduced by using seasonal transpiration instead of evapotranspiration to calculate water-use efficiency.

CHAPTER 8

THE INFLUENCE OF WATER REGIMES ON ROOT GROWTH

8.1 Introduction

The potato plant is known to have a shallow and poorly distributed root system, compared to crops like wheat and maize (Fulton, 1970). Shallow root systems reduce the volume of soil from which roots can extract water and nutrients (Miller & Martin, 1990; Incerti & O'Leary, 1990). Adequate soil water is required to ensure satisfactory yield and quality of potato tubers (Miller & Martin, 1990).

Root systems of actively growing plants continually explore new regions of soil. The most rapid water absorption is considered to occur from the zones of maximum rooting density near the soil surface (Fulton, 1970). When these layers dry out while deeper soil layers are still wet, the zone of maximum absorption then moves downward and outward. Water will mainly be absorbed from wet soil, until most available water from the root zone is depleted. Deep-rooted crops should therefore be able to extract water from larger soil volumes than shallow-rooted crops (Fulton, 1970).

The stimulation of deeper root systems by drought has been reported in the literature for many crops. Within the same species deeper root systems hold promise of better drought tolerance, presumably by being able to withdraw water from deeper zones between irrigations, which enables the plant to maintain its physiological processes. Ekanayake & Midmore (1992), using root-pulling resistance in combination with high yielding ability under water deficit conditions to classify the drought tolerance of potato genotypes, found a significant correlation (r=0.569***) between tuber yield and root-pulling resistance under conditions of moderate drought. This suggests that the pulling-resistance method can help in the selection of high-yielding, drought-resistant potato genotypes adapted to the tropics. Studies by Stalham & Allen

(1993) have shown that Cara, an indeterminate cultivar, has a deeper and more ramified root system than Desirè, and was able to utilise water from deeper soil zones, which enabled it to survive longer and produce higher yields than Desirè. The work of Jefferies & MacKerron (1993), however, has indicated that there was little difference in drought tolerance between these two cultivars. Local studies with the cultivar Up-to-date (unpublished data) have indicated that although drought resulted in slightly deeper root development, the majority of roots (>85%) occurred in the upper 600 mm soil layer. It therefore appears that, at least in this case, adaptation to water stress by the development of deeper roots was limited.

Root studies on potatoes are limited, as they are time consuming, tedious and often subjective (Harris & Campbell, 1989). Stimulated by promising results reported in the literature (Ekanayake & Midmore, 1992; Stalham, 1993), the present studies included the rooting response of various potato genotypes to different water regimes over a period of three years. The hypothesis was that genotypes that are able to develop deeper root systems in order to extract water from deeper soil layers will be more drought tolerant. If this proved to be true, such a trait might be a useful tool for selection in breeding programmes.

8.2 Materials and methods

Root data were collected from the 1993 spring until the 1995 autumn planting. Details of cultivation practices and water treatments applied are described in Chapters 3 and 4. As plots were small, measurements were limited to one sampling per season in order to reduce disturbance of the plants and soil profile. Sampling took place at the start of foliage senescence on one replication per trial, and only for the W1, W3 and W5 water treatments.

A steel sampling tube with hardened cutting tips (42 mm in diameter) was used to obtain the soil cores down to a soil depth of 1200 mm, similar to the method used by Incerti & O'Leary (1990) and Box & Ramseur (1993). Three cores from each plot were taken: two in the row 150 mm from the base of a plant, and one from the midpoint between two adjacent rows. The soil cores were divided into 300 mm segments and the three segments from corresponding depths were combined. These were sealed in plastic bags and stored in a deep freezer. Each sample was later washed over a 400 micron screen, using a specially designed cyclone water washer. Roots were collected and stored in phenoxy indole acetic acid (FAA), whereafter they were oven-dried at 50 °C for two days. Total length per root sample was measured by the line intersection method (Leskovar *et al.*, 1989; Chan & Mead, 1992), which is widely used because of its simplicity and accuracy (Harris & Campbell, 1989). Root concentrations were expressed as root length densities in units of km m^{-3}.

8.3 Results and discussion

Results of root length densities recorded for the various plantings are presented in Figures 8.1 to 8.6. No statistical analysis was conducted on the data as root samples were collected from one replication only.

Root densities generally decreased with increasing depth, with the highest concentration of roots in the first 300 mm soil layer. Between 70 - 85% of the roots occurred in the upper 600 mm zone, independent of genotype and water treatment. Studies by Fulton (1970) showed similar results: late in the season 60% of the roots were located in the top 680 mm of soil. Although variation in the data is evident, it is clear that water stress (W3 and W5 treatments) did not substantially stimulate rooting depth in any genotype or planting. In some instances the root densities in the deeper soil layers were higher in the wet treatments than in the dry treatments for the same genotype. Comparing the W1 and W5 treatments, it appears that for most genotypes and plantings the root densities in the shallowest layer (0 - 300 mm) were lower for the W5 treatments (Figures 8.1 to 8.6), but the trend is not consistent. This might indicate that some roots died as a result of the dry conditions in that zone.

Late Harvest, the standard late genotype, in most instances had higher concentrations of roots in the deeper zones than the genotypes to which it was compared in the same trial (e.g. Figures 8.3 and 8.5). Clear differences in deep-root penetration were not obvious between Up-to-date, the medium standard, and Late Harvest (figures 8.1 and 8.2). Up-to-date has been shown to

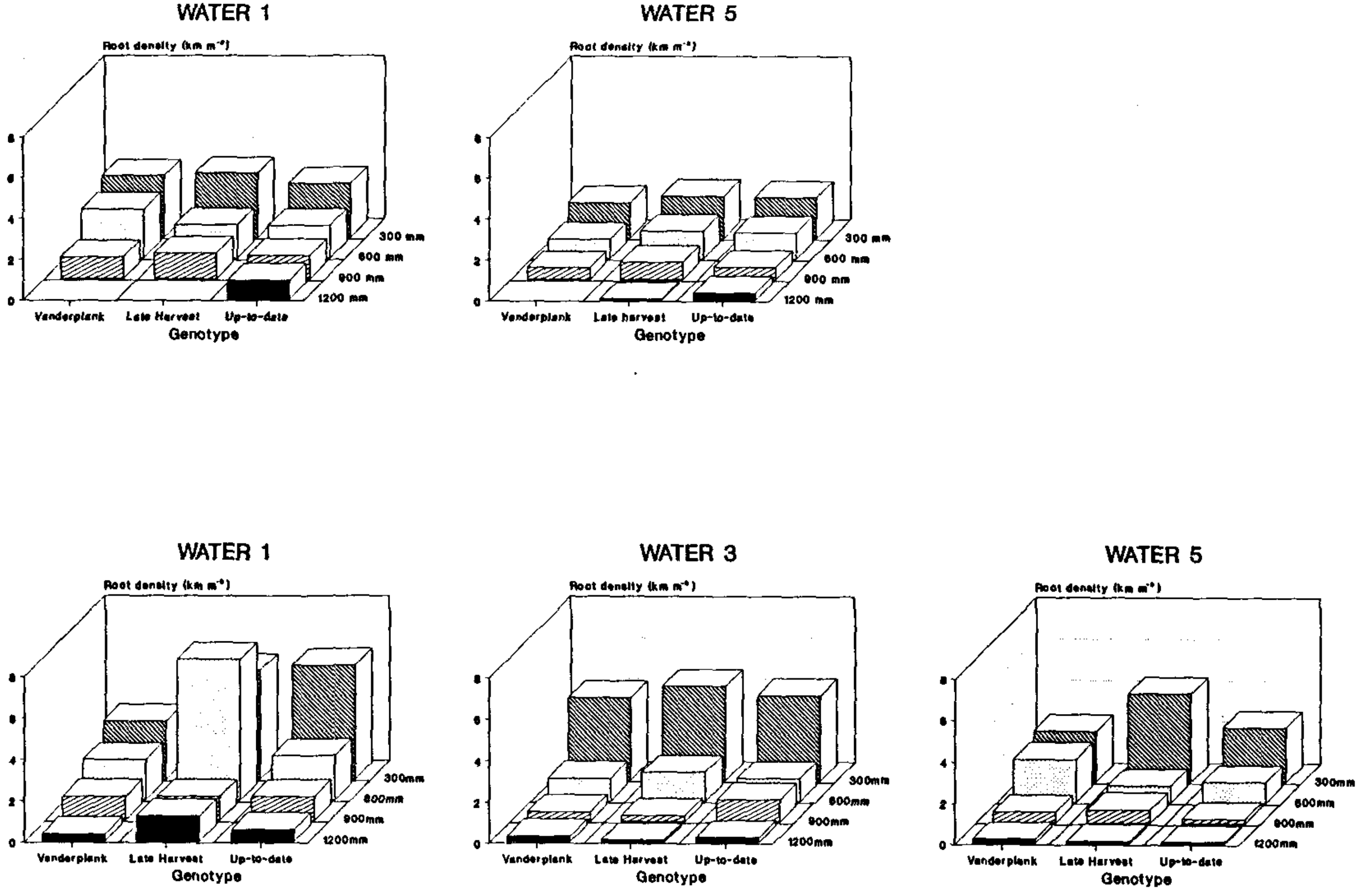


FIGURE 8.1 : Root densities of three potato genotypes during the 1992 spring (top) and 1993 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #1)

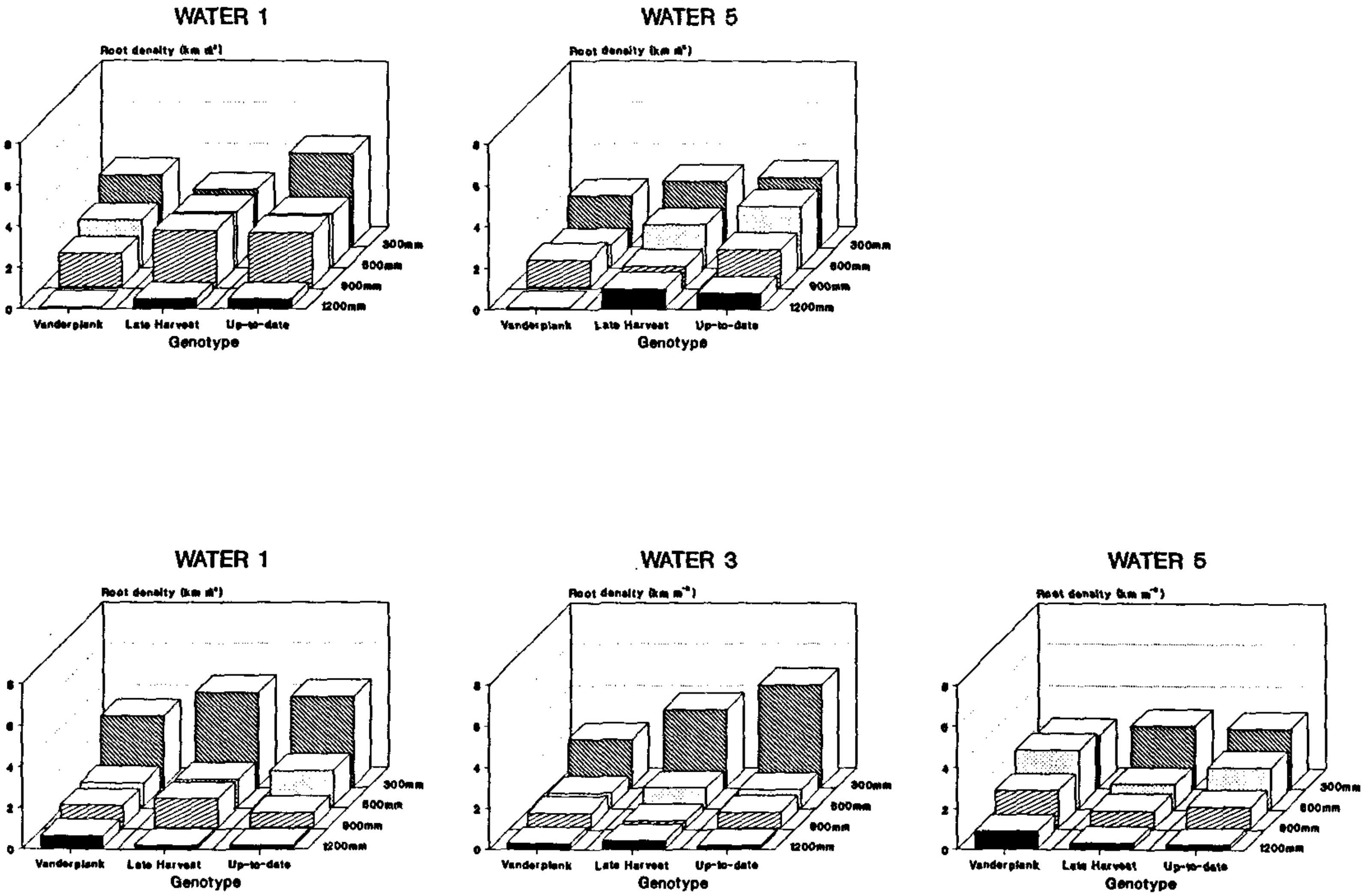


FIGURE 8.2 : **Root densities of three potato genotypes during the 1992 spring (top) and 1993 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #2)**

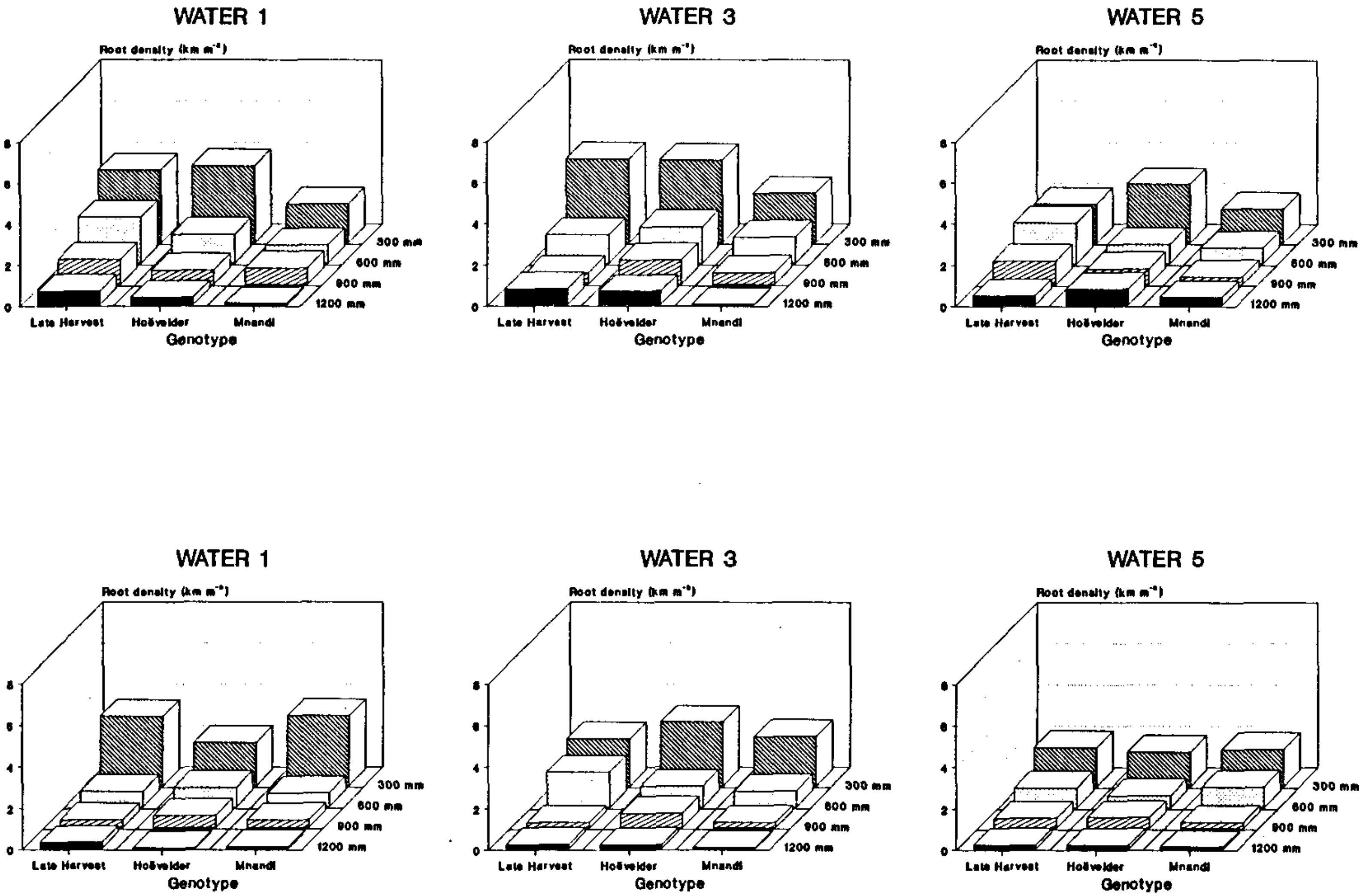


FIGURE 8.3 : Root densities of three late potato genotypes during the 1993 spring (top) and 1994 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #1)

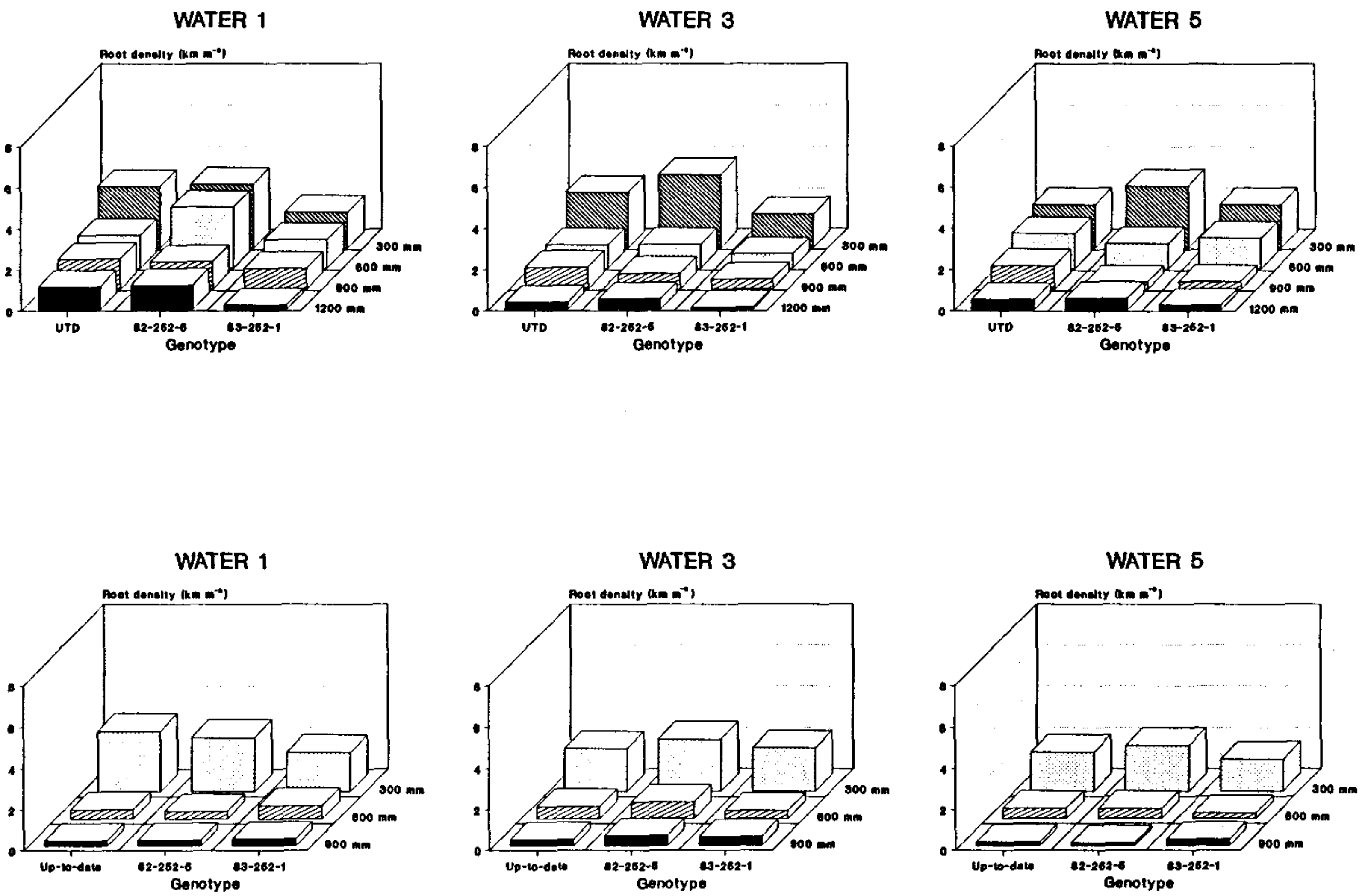


FIGURE 8.4 : **Root densities of three medium potato genotypes during the 1993 spring (top) and 1994 autumn season (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #2)**

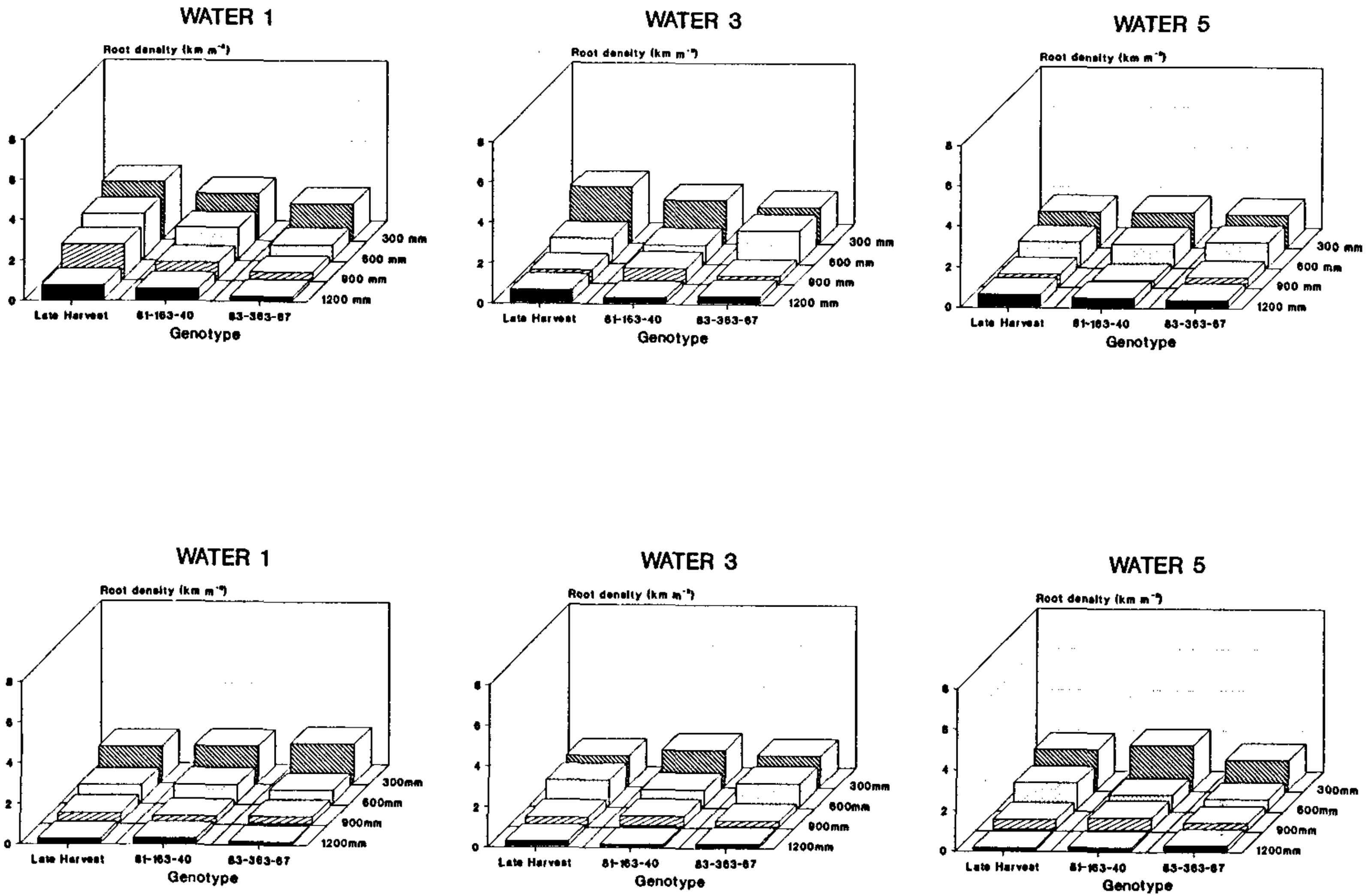


FIGURE 8.5 : Root length densities of three late potato genotypes during the 1994 spring (top) and 1995 autumn planting (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #1)

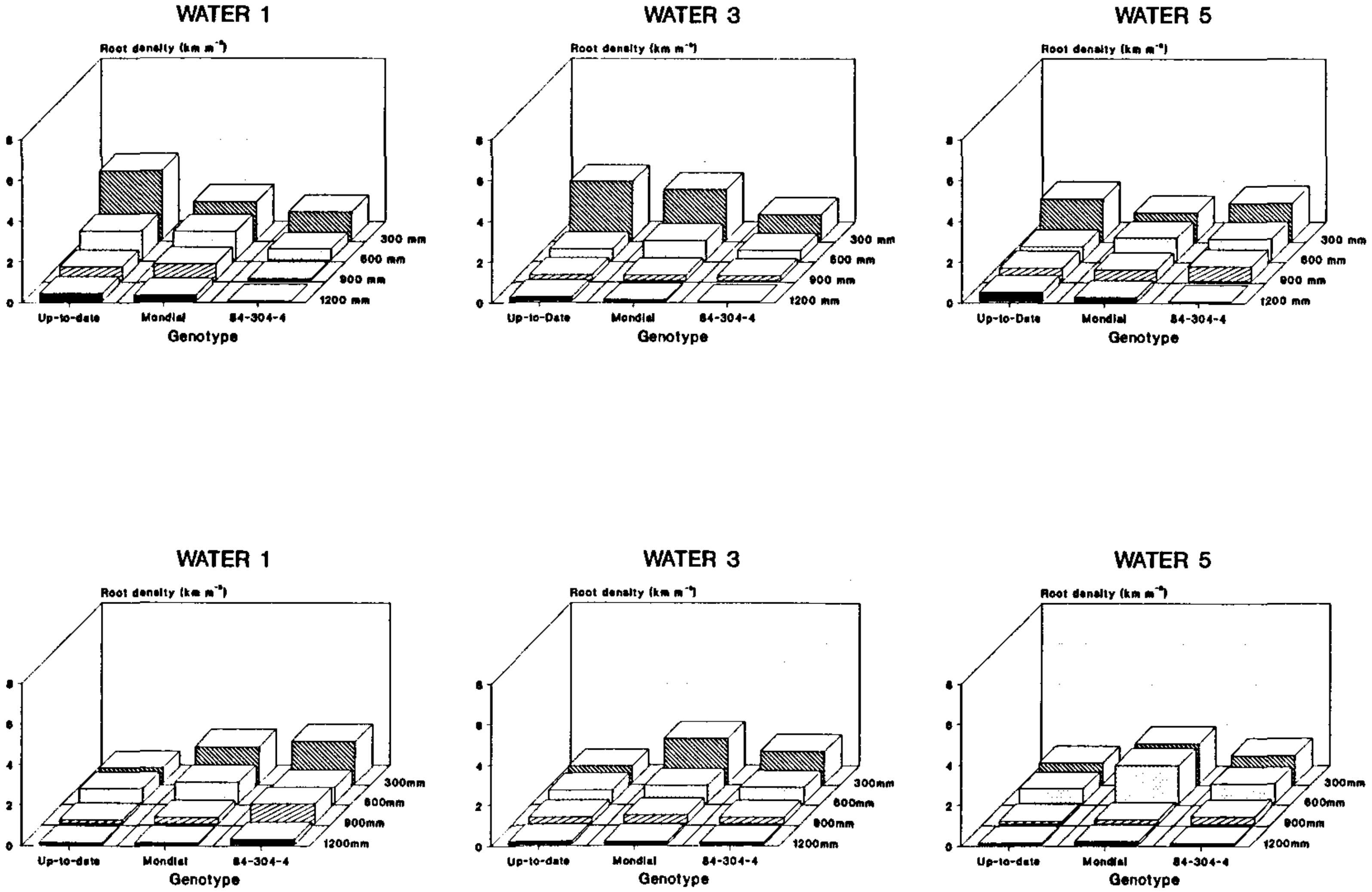


FIGURE 8.6 : Root length densities of three medium potato genotypes during the 1994 spring (top) and 1995 autumn planting (bottom) as influenced by water treatments W1, W3 and W5 (Rain shelter #2)

be more drought susceptible than Late Harvest (Chapters 4 and 9), suggesting a poor relationship between drought tolerance and root distribution. Also Mnandi, a high-yielding genotype, even when water stressed, appears to have had fewer deep roots than both Late Harvest and Hoëvelder (Figure 8.3).

The genotype 83-252-1 appears to have had less roots in total, compared to 82-252-5 and Up-to-date, especially in spring plantings (Figure 8.4). However, indications that both 82-252-5 and 83-252-1 are more drought-tolerant than Up-to-date are presented in Chapter 9. In studies carried out by Levy (1983a) Up-to-date also had an extensive root system, but produced the lowest yield of all the genotypes as a result of water stress and high ambient temperatures.

It is clear that while seasonal differences were small, it appears from Figures 8.3 to 8.6 that slightly more roots were formed in spring than autumn plantings. This trend may be attributable to the shorter growing season in autumn, but the lower evaporative demand and lower water use in autumn might have contributed to the smaller root systems.

Depth of root penetration seems to be genetically defined, as almost the same number of roots were present in the 1200 mm soil layer, independent of the soil-water status. It must be borne in mind that all the treatments started off with wet profiles, which allowed the same degree of root development early in the season. Fulton (1970) concluded that differences in soil-water regime necessary for maximum yield of potatoes cannot be explained by the position of the major part of the root system. He found that potato yield was affected by a relatively small stress applied to only a portion of the total root system and suggests that potato roots may have a relatively low capacity for water absorption, and that most of the root system must have access to water at low tension in order to produce maximum yield. This was confirmed by the present study, as very little water seems to be depleted from the soil layers below 900 mm (Figure 7.4), although roots were present in that zone.

8.4 Conclusions

This study has shown that, although deeper root systems should have access to greater volumes of soil from which more water can be exploited, water stress did not stimulate deeper root systems in the genotypes studied. Between 70 - 85% of the total root system was located in the upper 600 mm of soil, independent of the genotype and water treatment applied. Variation in the data was inevitable, as only one replication per treatment was sampled, but clear differences in the extent of root systems for different genotypes were evident. The size of the root system did not appear to correspond with other drought tolerance characteristics in the genotypes evaluated in this study. Some of the genotypes, such as Mnandi and 83-252-1 for example, had smaller root systems, but were more drought-tolerant than many of the other genotypes.

If root systems do play a role in drought tolerance, the capacity of some genotypes to withstand drought is perhaps due to total root surface area differences (Tan & Fulton, 1985), which were not investigated in this study, as only the total lengths of the thicker roots (> 400 micron) were collected and measured.

A practical implication of these findings for irrigation scheduling is that the same rooting depth can be used in the calculation of plant-available water for all potato genotypes. Although some roots were present in the deeper soil layers, their contribution to water uptake was limited (Chapter 7). A maximum rooting depth of 600 mm is suggested for the calculation of plant-available water in irrigated potatoes.

CHAPTER 9

A QUANTIFICATION OF THE DROUGHT TOLERANCE OF POTATO GENOTYPES

9.1 Introduction

The sensitivity of potatoes to water stress is well documented (Doorenbos & Kassam, 1979; Van Loon, 1981; Coleman, 1986; Van Loon, 1986; Miller & Martin, 1990). Significant reductions in tuber yield and quality, for example, are almost certain consequences of drought stress (MacKerron & Jefferies, 1988; Jefferies & MacKerron, 1993; Adams & Stevenson, 1990; Haverkort *et al.*, 1990).

It is generally accepted that better yield and quality can be attained by the selection of cultivars that are better adapted to specific environments, such as drought and heat (Cother *et al.*, 1981). The development of drought-tolerant potato cultivars is one of the major objectives in hot tropical environments, where there is insufficient soil water during the growing season (Demagante, Harris & Van der Zaag, 1995). Various physiological parameters have been evaluated as indices for the screening of drought tolerance. These include changes in photosynthetic rate, stomatal resistance or conductance, leaf water potential and canopy temperature (Dwelle *et al.*, 1981; Wilcox & Ashley, 1982; Dwelle, 1985; Coleman, 1986; Vos & Groenwold, 1988; Schapendonk *et al.*, 1989; Sukumaran *et al.*, 1989; Vos & Groenwold, 1989; Spitters & Schapendonk, 1990; and Chapter 6 of this study). Selection for drought tolerance is usually difficult to achieve as drought tolerance cannot easily be related to one or more morphological or physiological aspects (Spitters & Schapendonk, 1990). Whether physiological screening methods are successful or not, it seems that field evaluations will always be necessary to verify the drought tolerance of genotypes.

Limited water is a major restriction to crop production in South Africa, as in many other semi-arid parts of the world. Therefore, the breeding of genotypes better adapted to drought is an important priority of the local potato breeding programme. This chapter deals with the evaluation for drought tolerance of potato cultivars and breeding lines used in the water-use trials discussed in Chapters 3 and 4.

9.2 Materials and methods

Classification of drought tolerance is usually based on relative tuber yield or yield reduction as a result of drought stress (Mahalakshmi *et al.*, 1990; Price, Jalaludden & Dilday, 1992; Jefferies & MacKerron, 1993; Demagante *et al.*, 1995). Tuber yield in water-limiting conditions is expressed as a percentage of yield produced with an abundant supply of water (Price *et al.*, 1992; Demagante *et al.*, 1995). Fischer & Mauer (1978) suggested a "drought-sensitivity index" to compare drought tolerance of genotypes. This index gives the reduction in yield of a specific genotype due to water stress relative to the average yield reduction observed for all the genotypes in that trial. The most drought tolerant genotype will therefore be the one with the lowest reduction in yield. The index is calculated with the following equation:

$$\mathbf{DSI = (1\text{-}Yd/Yw)/(1\text{-}\underline{Yd}/\underline{Yw})} \tag{9.1}$$

where

Yd = stressed yield of genotype

Yw = unstressed yield of genotype

$\underline{Yd}$ = mean stressed yield of all genotypes

$\underline{Yw}$ = mean unstressed yield of all genotypes

An index value greater than 1 indicates drought sensitivity relative to the mean, while a value less than 1 indicates drought tolerance. Since genotypes were compared over seasons (Chapter 4), it was decided to express the yield loss of genotypes relative to the yield loss recorded for the standard genotype in the same trial, rather than the mean. The mean of the combined yields for W1 and W2 were used to represent the unstressed yields, and the mean of the combined yields for W4 and W5 represented the stressed yields. Equation 9.1 was subsequently changed to the following:

$$\mathbf{DSI = (1\text{-}Yd/Yw)/(1\text{-}Yds/Yws)} \qquad (9.2)$$

where

Yd = stressed yield of genotype, averaged for W4 and W5
Yw = unstressed yield of genotype, averaged for W1 and W2
Yds = mean stressed yield of standard genotype, averaged for W4 and W5
Yws = mean unstressed yield of standard genotype, averaged for W1 and W2

This method established a baseline for comparison, as the drought tolerance characteristics of the standard genotypes are known: Late Harvest, the late season standard, is a drought-tolerant local cultivar (Van der Mescht *et al.*, 1992; Rossouw & Waghmarae, 1995), while Up-to-date, the medium-season standard, is known to be fairly drought-sensitive, especially in hot climates (Levy, 1983a; Levy, 1983b; Jefferies & MacKerron, 1993). For the late-maturity class, index values =1 (the same as Late Harvest) or < 1 will indicate drought tolerance. Index values =1 for the medium-maturity class indicate drought-sensitivity similar to that of Up-to-date, while values <1 indicate better drought tolerance than Up-to-date.

9.3 Results and discussion

Drought-sensitivity indices (DSI) as well as percentage yield reduction for the medium- and late-maturity classes are presented in Tables 9.1 and 9.2, respectively. During the 1992 trials genotypes of both medium- and late-maturity classes were cultivated together under the same rain shelter. Since the 1993 spring planting genotypes were separated according to maturity class (see Chapter 3 for details). As the effect of drought on tuber yield was more severe in spring, the indices for spring and autumn plantings are presented separately in the tables.

TABLE 9.1 : Drought sensitivity indexes (DSI) and percentage yield reduction recorded for different genotypes in the late maturity class during spring and autumn plantings

Genotype	Planting	DSI*	% Yield** reduction	Planting	DSI	% Yield reduction
Late Harvest	Spring	1.000	59.7	Autumn	1.000	53.0
Up-to-date	1992	1.397	83.4	1993	1.034	54.8
Vanderplank		1.125	67.2		1.141	60.5
Late Harvest	Spring	1.000	62.9	Autumn	1.000	56.8
Hoëvelder	1993	1.120	70.5	1994	1.009	57.3
Mnandi		1.024	64.4		1.079	61.0
Late Harvest	Spring	1.000	53.1	Autumn	1.000	36.2
81-163-40	1994	1.277	67.9	1995	1.039	37.6
83-363-67		1.215	64.6		1.131	40.9
Average			66.0			50.9

* Drought sensitivity index, expressed relative to Late Harvest in the same trial

** % Yield reduction of each genotype, expressed relative to its own unstressed yield

TABLE 9.2 : Drought sensitivity indexes (DSI) and percentage yield reduction recorded for different genotypes in the medium maturity class during spring and autumn plantings

Genotype	Planting	DSI*	% Yield** reduction	Planting	DSI	% Yield reduction
Up-to-date	Spring	1.000	70.01	Autumn	1.000	38.5
Late Harvest	1992	0.853	59.8	1993	0.989	38.1
Vanderplank		0.737	51.7		0.811	31.2
Up-to-date	Spring	1.000	80.4	Autumn	1.000	30.2
82-252-5	1993	0.811	65.2	1994	0.964	29.2
83-252-1		0.850	68.3		0.879	26.6
Up-to-date	Spring	1.000	77.7	Autumn	1.000	34.2
Mondial	1994	1.004	78.0	1995	1.255	43.0
84-304-4		0.851	66.1		1.194	40.9
Average			68.6			34.7

* Drought sensitivity index, expressed relative to Up-to-date in the same trial

** % Yield reduction of each genotype, expressed relative to its own unstressed yield

From Tables 9.1 and 9.2 it is clear that the effect of drought was most severe in spring plantings, when the atmospheric evaporative demand was highest (Figure 3.1). For the late-maturity class, the genotypes Up-to-date, 81-163-40 and 83-363-67 were most drought-sensitive during spring plantings, while Vanderplank, Hoëvelder and Mnandi had DSI values only slightly greater than 1. In autumn plantings almost no genotypic differences in DSI values were evident, indicating that the direct effect of high temperatures or the combined effect of both high temperatures and high evaporative demand were mainly responsible for the differences. For the medium- maturity class all the genotypes were more drought-tolerant than the standard Up-to-date in both spring and autumn plantings, with the exception of Mondial (both plantings) and 84-304-4 (autumn). Since 84-304-4 did not experience normal growing conditions, as discussed earlier, no conclusions should be drawn from its performance in any trial. DSI values in autumn were closer to 1, indicating that the effect of stress was also less prominent than in spring plantings.

Late Harvest and Vanderplank, as well as the two breeding lines 82-252-5 and 83-252-1, had indices markedly less than 1 in spring plantings, indicating their better drought tolerance relative to Up-to-date. These results agree with the conclusions drawn in Chapter 4 regarding the ranking of genotypes according to their relative yields: in spring plantings, ranking according to relative yields depended on the water treatment, suggesting genotypic differences in their ability to cope at different levels of water stress, while in autumn the ranking did not change.

The very important difference between the meaning of the "relative tuber yields" (Chapter 4) and DSI's discussed in this chapter should be emphasized. The ranking of genotypes according to relative tuber yields deals with the physical yields obtained and does not take into account the reduction in yield due to water stress. Mnandi, for example, did not differ much from Late Harvest regarding its drought tolerance (DSI), but was constantly ranked higher than Late Harvest because of higher yields than Late Harvest recorded for all the water treatments. The ranking according to yield will therefore be the most useful criterion to producers selecting genotypes most suitable to their conditions, while the DSI will be of most value to plant breeders selecting for drought-tolerant parental material.

9.4 Conclusions

The effect of drought on tuber yield was most severe in spring plantings, when the atmospheric evaporative demand was highest. The late-maturity genotypes 81-163-40 and 83-363-67 were most drought-sensitive, while Hoëvelder and Mnandi compared favourably to Late Harvest, the drought tolerant standard. Vanderplank, 82-252-5 and 83-252-1 are the most drought tolerant and Up-to-date the most drought sensitive genotype in the medium-maturity class.

Genotypic differences in DSI-values were almost non-existent in autumn plantings, indicating that the effects of both high temperatures and high evaporative demand were mainly responsible for the differences in spring plantings.

The ranking of genotypes according to yield (Chapter 4) will be a useful criterion to producers selecting genotypes most suitable for their conditions, while the drought sensitivity indices (DSI) discussed in this Chapter will be of most value to plant breeders, who are selecting for drought-tolerant parental material.

CHAPTER 10

CALIBRATION AND EVALUATION OF THE SOIL WATER BALANCE (SWB) MODEL

10.1 Introduction

Limited water resources are a problem for most production sectors in South Africa. Irrigated agriculture is perceived to be the most inefficient of major water users. This is of major concern to farmers, including potato producers, who are dealing with a very drought-sensitive crop. Optimal use of irrigation water is only achieved by the application of effective irrigation scheduling. According to surveys carried out among potato producers, irrigation scheduling was consistently listed as an important yield-limiting factor (PPO, 1995). It is, however, also evident that most irrigators do not schedule irrigations (Annandale, *et al.*, 1996) and base their decision of when and how much to irrigate on experience only. There could be many reasons for this trend but Annandale *et al.* (1996) have concluded that the majority of farmers do not expect a net benefit from applying irrigation scheduling technology. A lack of simple, quick and reliable irrigation scheduling techniques seems to be another important reason why farmers do not schedule irrigations.

Direct measurement of soil-water content gives the best estimate of plant water use, but this method is usually time consuming, requires calculations and is often impractical on a large scale. Other methods, like A-pan evaporation in combination with crop factors and estimations from long-term evaporation (Green, 1985) are season-dependent and may not be reliable (Annandale & Stockle, 1994). The A-pan and crop factor-method assumes that crop development is dependent only on calendar time and that water use is determined only by atmospheric demand, which is certainly not the case (Campbell, 1977). Crop development is mainly dependent on thermal time but is also influenced by other factors such as water supply and evaporative demand. Water use is not only dependent on atmospheric demand, but also on the supply of water from the soil-root system (Annandale *et al.*, 1996).

User-friendly irrigation scheduling models may fulfill the need for irrigation management aids, as they mechanistically integrate our understanding of the soil-plant-atmosphere continuum. The many models available for soil-water budgeting differ greatly in their complexity, in the inputs needed and in their degree of accuracy (Kruse, Ells & McSay, 1990; Larsen *et al.*, 1984). In order to make accurate estimates of plant water use, the model should grow a realistic canopy and root system, split potential evaporation and transpiration and take the water supply from the soil-root system, as well as the demand from the canopy-atmosphere-system into account.

Penman-Monteith reference crop evaporation used in combination with a mechanistic crop growth model will provide a good estimate of the soil-water balance. Due to the specialist knowledge and inputs required to follow this approach, it has previously been out of reach of most irrigators on farm level. The ideal model would therefore require a simple interface for the user, while still using an accurate mechanistic approach which will ensure reliable simulations.

The aim of this chapter was to calibrate a generic crop irrigation scheduling model, the Soil Water Balance (SWB) model (Annandale *et al.*, 1996; Benade, Annandale & Van Zijl, 1996) for potato crops and to evaluate its performance on an independent data set.

10.2 Model description

The SWB model is based on an improved version of the model described by Campbell & Diaz (1988). The model is briefly discussed, with a more detailed description presented by Campbell & Stockle (1993).

The generic crop model is user-friendly and simple to operate, yet a mechanistic rather than empirical approach is followed in order to adhere to the accuracy required and to achieve a degree of transferability. Crop dry-matter production is calculated from the amount of transpiration, since yield is directly related to transpiration (corrected for vapour pressure deficit) in high-radiation climates (Tanner & Sinclair, 1983; Tan & Fulton, 1985):

$$\mathbf{Y = k\,T\,/\,VPD} \qquad \mathbf{(10.1)}$$

where Y is the dry matter produced (kg m^{-2}), k is a crop-specific constant (kPa) (the vapour pressure deficit corrected dry matter:water ratio), T is transpiration (kg m^{-2} or mm) and VPD the vapour pressure deficit of the atmosphere (kPa).

Dry matter production is also related to radiation intercepted by the foliage. The model calculates both the radiation- and water-limited growth on a daily time step and accepts the lesser of the two.

The dry matter produced is partitioned between roots, stems, leaves and harvestable yield. Preferential partitioning of assimilates to the different plant organs is dependent on phenological stage, which is calculated from thermal time and influenced by water stress. When the plants are exposed to water stress, assimilates are partitioned in favour of the roots, stimulating root growth at the cost of leaf expansion. Water stress conditions result therefore in smaller canopies and senescence is also enhanced.

A multi-layer soil component is used, which ensures a realistic simulation of the infiltration and crop water-uptake processes. A cascading soil water balance is used. When measurements of soil-water content or canopy fractional interception are made during the season, these can be entered into the model and the simulation will be corrected.

Potential evapotranspiration is divided into potential evaporation and potential transpiration by calculating radiant interception from the simulated leaf area. This represents the upper limits of evaporation and transpiration, which will only proceed at these rates if atmospheric demand is limiting. If actual transpiration, relative to potential transpiration, is less than the specified stress index, the crop is considered to be water stressed.

Transpiration rate depends on the atmospheric evaporative demand, soil-water potential and fractional interception of solar radiation by the crop canopy. Fractional interception (FI) is calculated from the leaf area index (LAI), using eq. 10.2:

$$\mathbf{FI = 1 - \exp(-Kc\ LAI)} \qquad \mathbf{(10.2)}$$

where Kc represents the solar radiation extinction coefficient, a crop-specific constant. Leaf area index is calculated from the dry matter partitioned to the crop canopy (eq.10.3). Canopy dry matter (CDM) consists of the total mass (kg m^{-2}) of stems and leaves. The leaf-stem partitioning factor p (m^2 kg^{-1}) describes the ratio of dry matter partitioned between the leaves and stems.

$$\mathbf{LAI = SLA\ CDM\ /\ (1+p\ CDM)} \qquad \mathbf{(10.3)}$$

SLA represents the specific leaf area, or the leaf area per unit dry mass of the leaves (m^2 kg^{-1}).

10.3 Inputs required

As the model is fairly simple, the input data required are limited and usually easily obtainable (Annandale *et al.*, 1996). The following soil, crop and daily weather inputs are required:

1. ***Soil parameters*** needed for each soil layer:

    1.1 volumetric water content at field capacity
    1.2 volumetric water content at permanent wilting point
    1.3 initial water content

2. *Crop parameters:*

2.1 cardinal temperatures (base and optimum temperatures for development in °C)
2.2 thermal time requirements (in degree days) for
  - emergence
  - onset of the reproductive stage
  - transition period
  - leaf senescence
  - crop maturity
2.3 VPD corrected dry matter:water ratio (kPa) (Tanner, 1981)
2.4 maximum rooting depth (m)
2.5 canopy solar radiation extinction coefficient (Kc)
2.6 radiation use efficiency (kg MJ^{-1})
2.7 assimilate partitioning parameters
2.8 maximum crop height (m)

3. *Weather parameters*

3.1 maximum and minimum temperatures (°C)
3.2 precipitation (and irrigation) (mm)
3.3 solar radiation (MJ m^{-2} d^{-1})
3.4 vapour pressure (VP) *or* minimum and maximum humidity *or* wet and dry bulb temperatures
3.5 wind speed (m s^{-1}) and height of measurement (m)
3.6 latitude and altitude

The minimum weather data required are daily minimum and maximum temperatures. If not available, the other parameters are estimated according to the FAO recommended method (Smith, 1992) to enable the calculation of reference crop evapotranspiration (ETo).

10.4 Model calibration and evaluation

Calibration

Data sets containing complete growth analysis data which were collected from previous trials (1987 and 1990 autumn plantings) with the cultivar Up-to-date were used to obtain some of the crop parameters, as well as for model calibration. Thermal time requirements for the different phenological stages, radiation-use efficiency, specific leaf area and leaf-stem partitioning factors were calculated from these data. Parameters which could not be derived from the data sets were obtained from the literature or estimated. The crop parameters used in subsequent simulations are listed in Table 10.1.

Model outputs for the calibration data sets of root growth, LAI, total dry matter (TDM), harvestable dry matter (HDM) and simulated soil-water deficits are plotted along with observed values in Figures 10.1 and 10.2. Canopy size (LAI), dry matter production and soil-water deficits were simulated to an acceptable degree of accuracy for the well-watered treatment. For water-stressed conditions, however, tuber dry matter and total dry matter production are somewhat over estimated, although the LAI and soil-water deficit simulations were close to the observed values.

TABLE 10.1 : Crop parameters used for the cultivar Up-to-date as derived from data (autumn plantings) and the literature

Parameter	Value	Units	Method of estimation *
Canopy extinction coefficient (Kc)	0.55	-	Johnson *et al.* (1988)
Dry matter:water ratio (dwr)	6.80	Pa	Tanner (1981)
Radiation use efficiency (RUE)	0.00175	kg MJ^{-1}	Trebejo *et al.* (1990); Data
Base temperature (Tb)	2	°C	MacKerron & Waister (1985)
Light limited temperature	10	°C	-
Optimum temperature (Tm)	22	°C	Kooman (1995)
Thermal time : emergence	350	day degree	Data
Thermal time : reproductive phase	750	day degree	Data
Thermal time : maturity	2300	day degree	Data
Thermal time : transition	250	day degree	Data
Thermal time : leaf senescence	900	day degree	Data
Leaf water potential at maximum transpiration rate	-550	kPa	Data
Maximum transpiration rate	7	mm day^{-1}	Data
Specific leaf area	20.5	m^2 kg^{-1}	Data
Leaf-stem partitioning factor	2.0	m^2 kg^{-1}	Data
Total dry matter at emergence	0.005	kg m^{-2}	Data
Root fraction	0.10	-	-
Stem translocation	0.45	-	-
Root growth rate parameter	2.2	m^2 $kg^{-0.5}$	-
Depletion allowed:			
Emergence	50	%	Data
Vegetative	50	%	Data
Reproductive	50	%	Data
Maximum rooting depth	0.6	m	Data
Maximum canopy height	1	m	Data

* Model default values were used for parameters not obtained from literature or data.

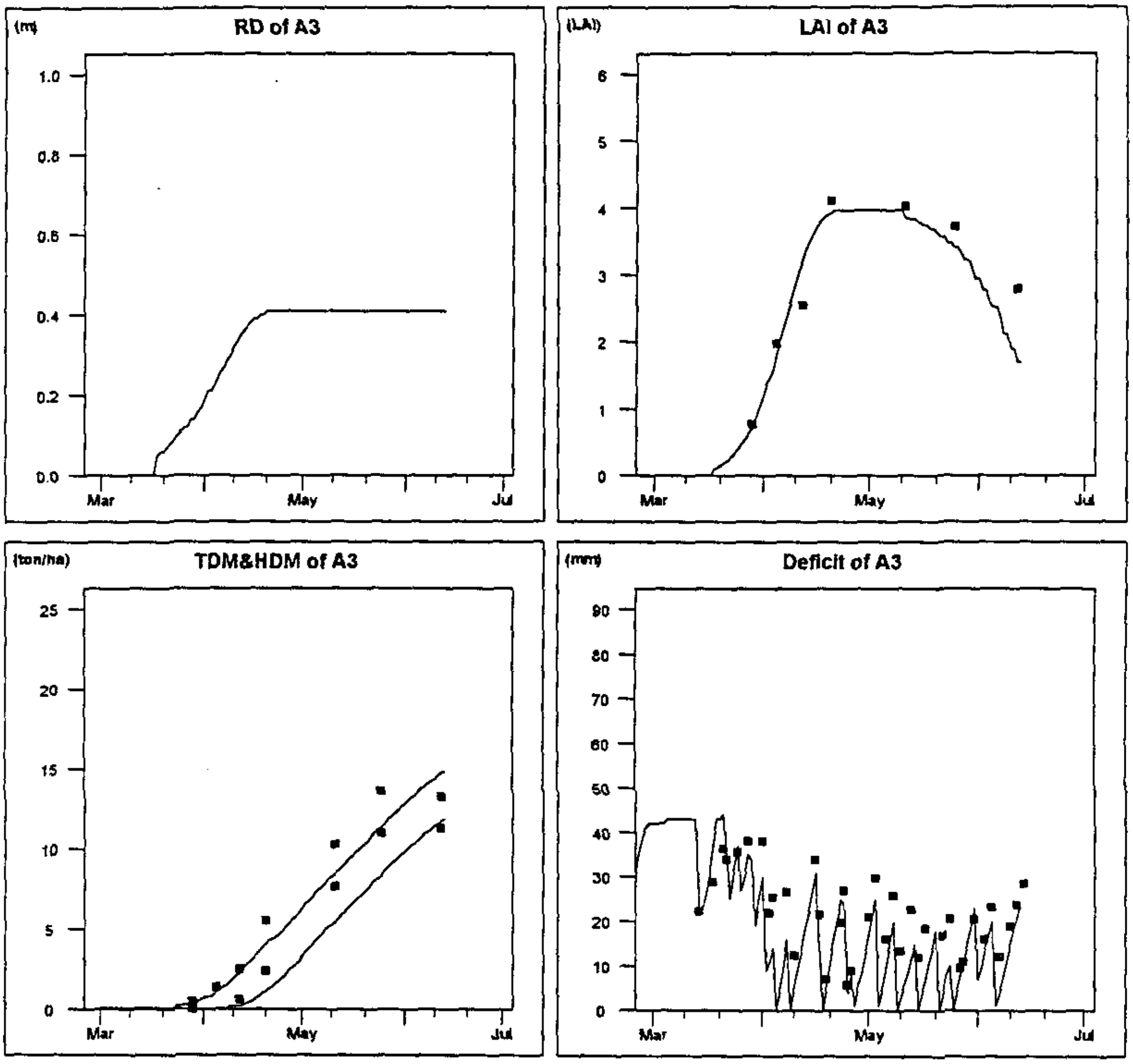


FIGURE 10.1 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for the calibration data set (autumn) of an unstressed potato crop

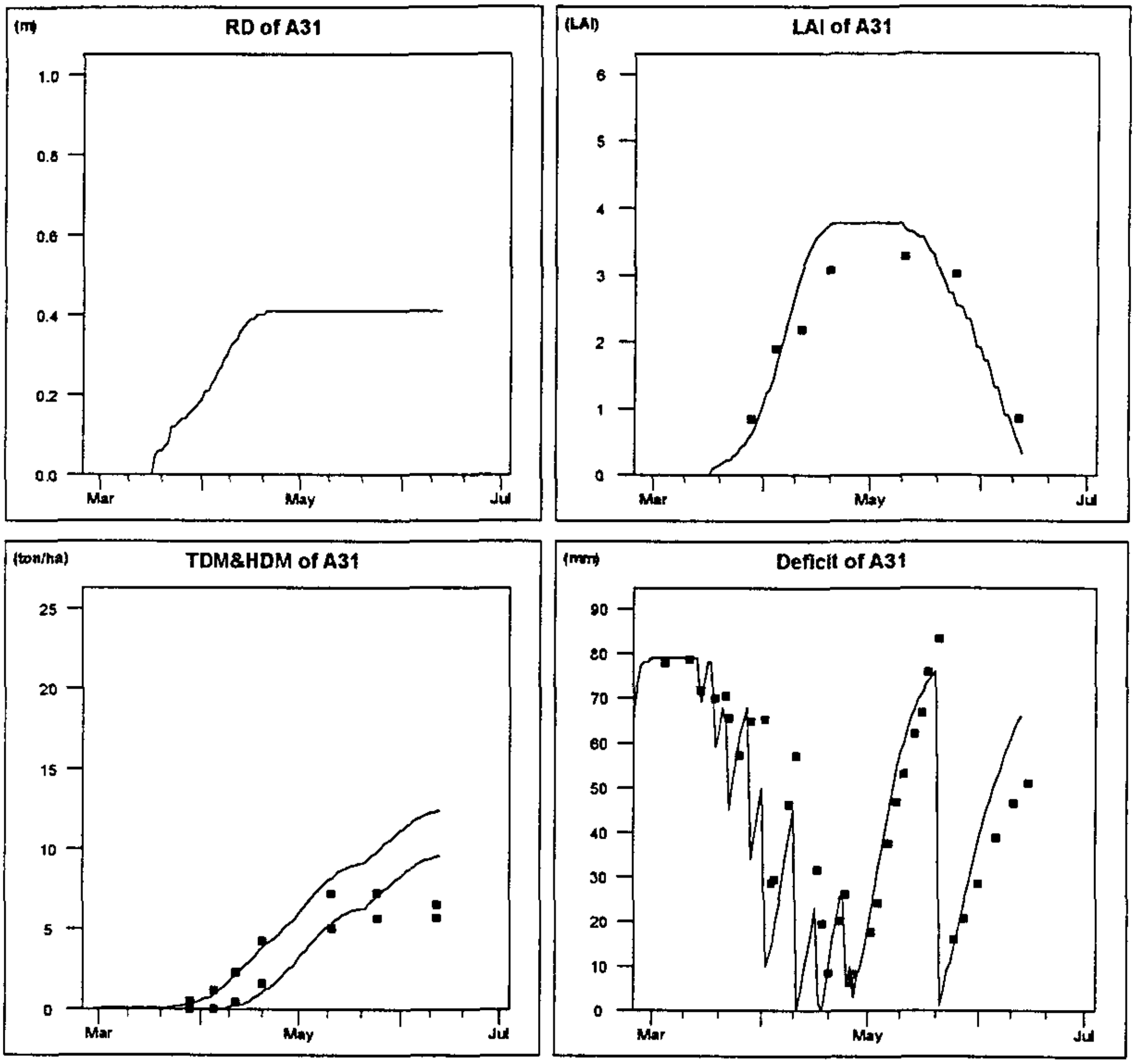


FIGURE 10.2 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for the calibration data set (autumn) of a water-stressed potato crop

Evaluation

Model evaluation was conducted on data sets for the Up-to-date cultivar, collected from the 1992 autumn and 1993 spring plantings of this project. Two irrigation treatments, a well-watered control (W1) and a water stressed treatment (W4 or W5) were used in the evaluation of the model.

Measurements were not made for some of the simulated parameters during this study. Dry matter accumulation of the different plant organs could, for example, not be determined as the number of replications was limited and plots were too small to conduct destructive growth analyses during the growing season. Total top dry matter and tuber dry matter were therefore determined only at the end of the growing season. Fractional solar radiation interception was measured three times during the 1993 spring planting only. For all the plantings soil-water content was recorded approximately three times per week.

Simulation outputs for both unstressed and water-stressed conditions, using the 1992 autumn data set, are presented in Figures 10.3 and 10.4. Only soil-water content and final tuber yield at harvest were recorded for this planting. Simulations pertaining to the accumulation of tuber dry matter and daily soil-water deficits were fairly accurate for both water treatments during this planting. This was also proved by the validation statistics carried out on the data (Table 10.2). It did, however, appear that the simulated LAI reduction at the end of the season was too rapid, as the simulated soil-water deficits for the last period were smaller than the measured values. As LAI was not measured, this could unfortunately not be confirmed.

The same crop parameters established from data collected during autumn plantings were used in the simulations for the 1993 spring planting. Maximum LAI, tuber dry matter and total dry matter production was under estimated and the simulated date of senescence was about one month earlier than the observed date (Figure 10.5). The smaller simulated canopy size also resulted in lower than measured values for water-use and soil-water deficits.

Growing conditions are known to be completely different during spring and autumn plantings:

in the spring crops are planted when temperatures are low and day lengths relatively short and the crop grows into hot, long day conditions towards senescence. The situation in autumn is completely the opposite to that for spring plantings: planting occurs in February, when temperatures are high and days are long, and the potato crop grows into cooler, short day conditions, until it is killed off by frost from middle May to early June (see Figure 3.1, Chapter 3 for long term climate of the trial site). The influence of photoperiod and temperature on potato development and the distribution of assimilates are known. Longer days postpone the onset of tuber initiation, enhance branching and extend the life cycle of potato plants, while short day conditions stimulate tuber initiation, reduce vegetative growth and lead to earlier senescence (Kooman & Haverkort, 1995). Temperatures also influence the partitioning of assimilates, especially in heat-sensitive genotypes, such as Up-to-date (Leskovar *et al.*, 1989; Wolf *et al.*, 1989). Under the high temperature conditions experienced during summer months (spring plantings) assimilates are partitioned in favour of haulm production at the expense of tuber growth, resulting in larger canopies and extended growth periods. Since SWB is a generic crop model, which does not take the effects of day length on crop growth and development into account, simulation errors in this regard should be expected.

Model performance could be enhanced by either adapting SWB to simulate these effects or, as a short term alternative, different sets of parameters could be developed for the two different plantings. After parameters such as the thermal time requirements for the different phenological stages were prolonged (reproductive phase 850 °Cd, maturity 2500 °Cd, transition 500 °Cd and leaf senescence 1300 °Cd) , simulations of tuber and total dry matter production, fractional interception of solar radiation (FI) and soil-water deficits improved considerably for unstressed conditions (Figure 10.6 and 10.8). For water-stress conditions, however, dry matter production and FI were under estimated (Figures 10.7 and 10.8).

Although leaf-area index was not measured, the simulated date of crop senescence was clearly far too early: the simulated leaf area index of the stressed treatment dropped to zero by late November, almost three weeks before the recorded date of haulm death. A proper calibration of the model for conditions in spring plantings could not be conducted, owing to the lack of complete data sets of crop development for such seasons.

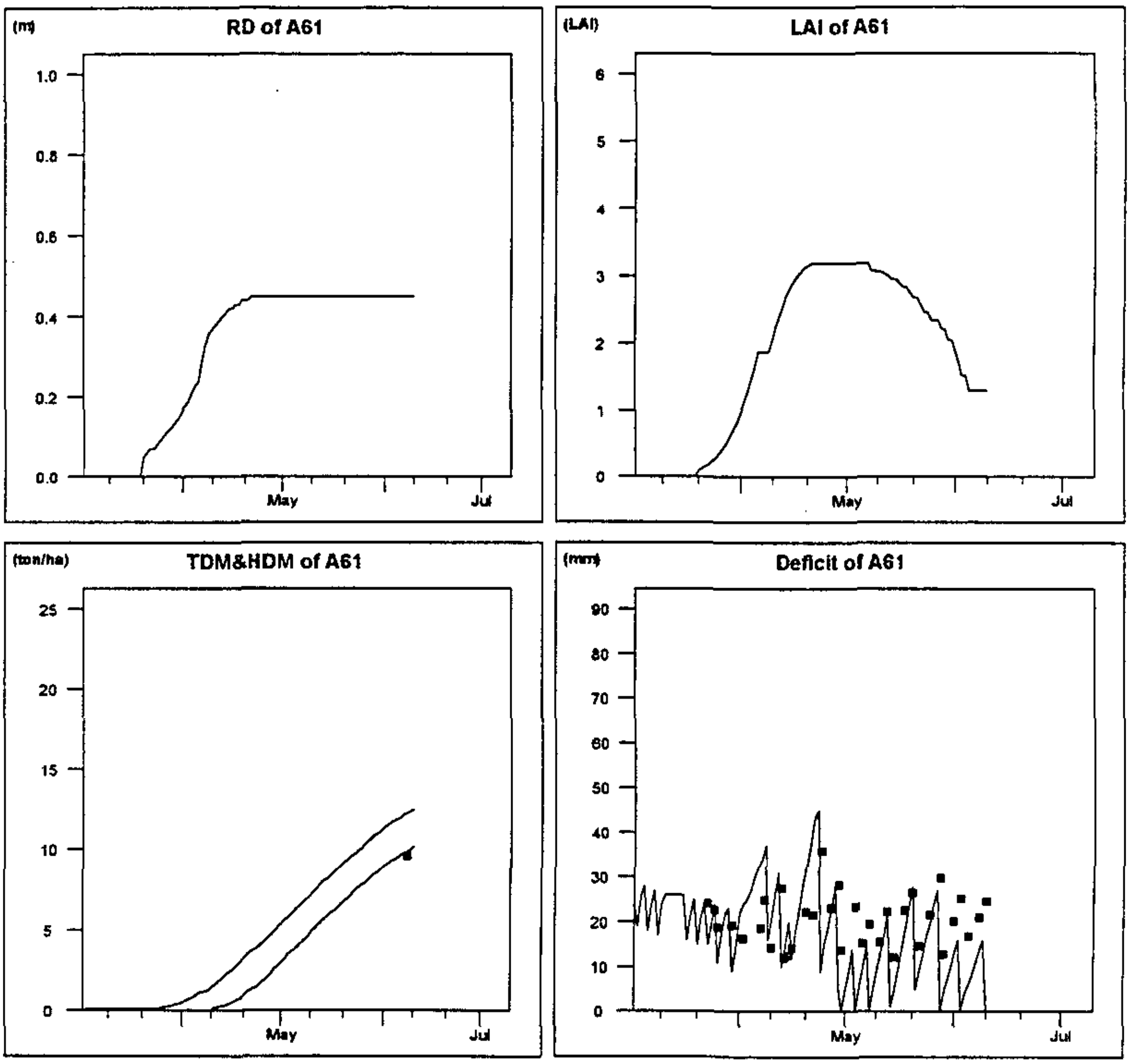


FIGURE 10.3 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for an independent data set (autumn) of an unstressed potato crop

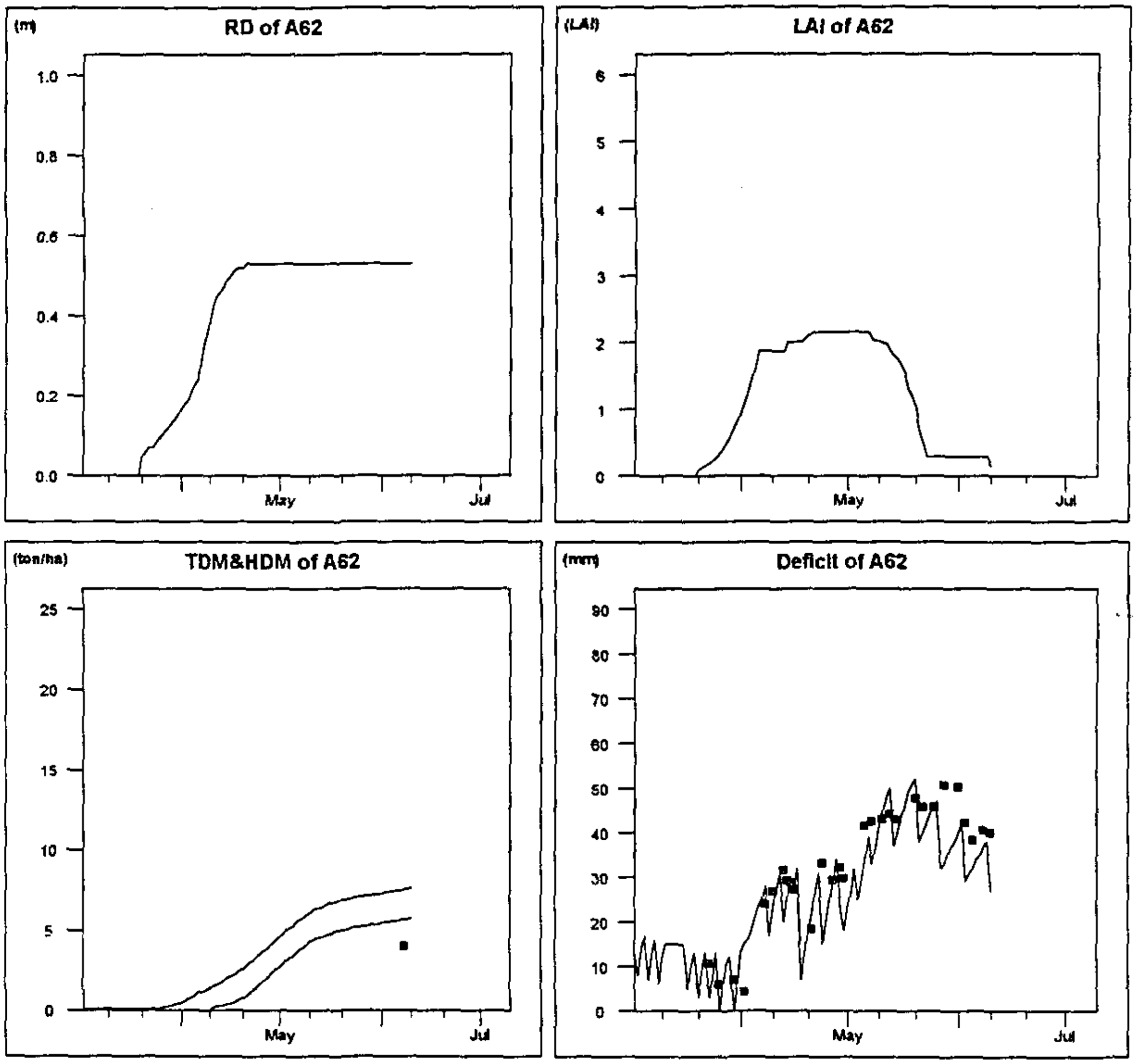


FIGURE 10.4 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm) for an independent data set (autumn) of a water-stressed potato crop

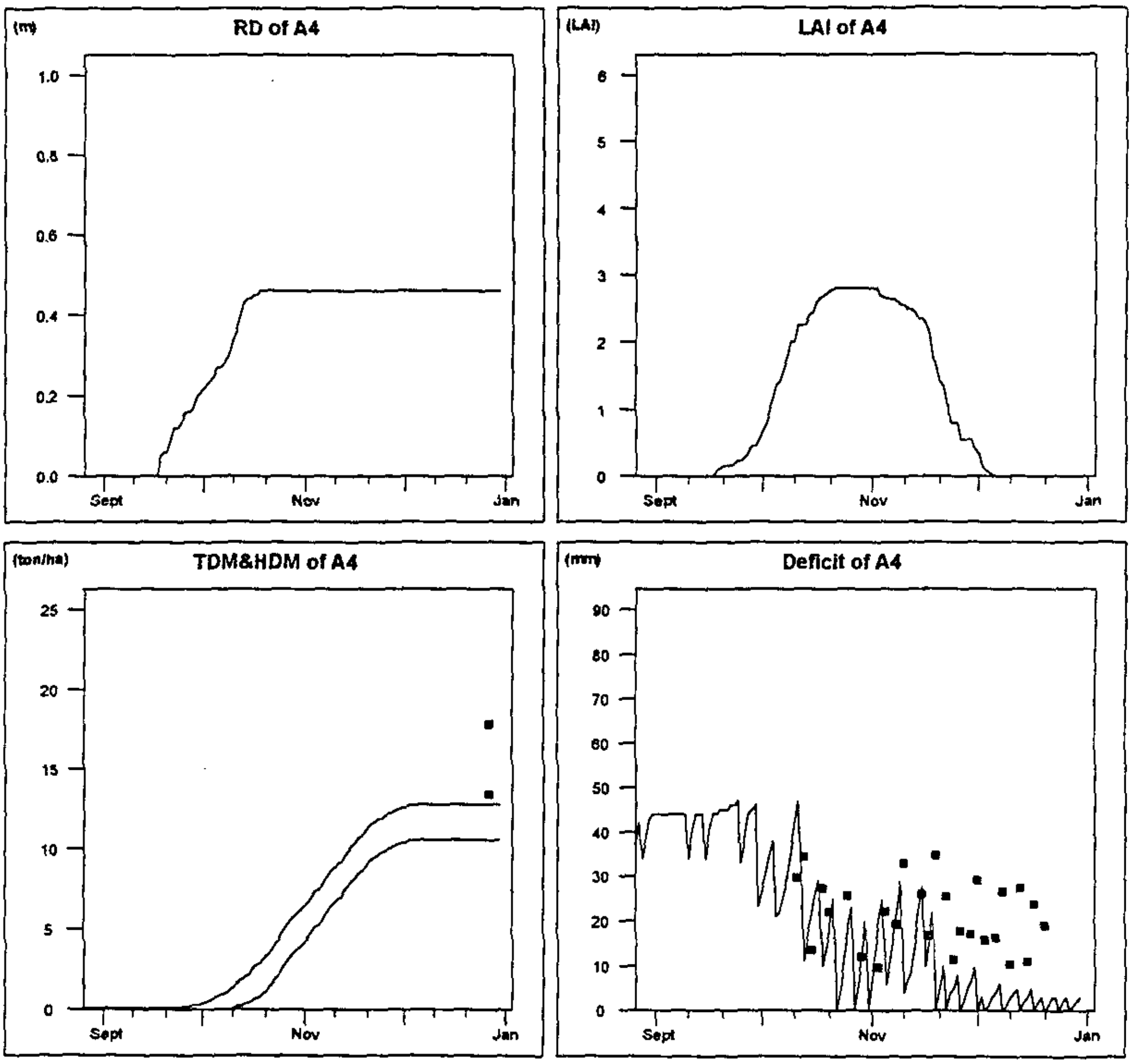


FIGURE 10.5 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm). Independent data set of an unstressed potato crop in the 1993 spring season with crop parameters for autumn

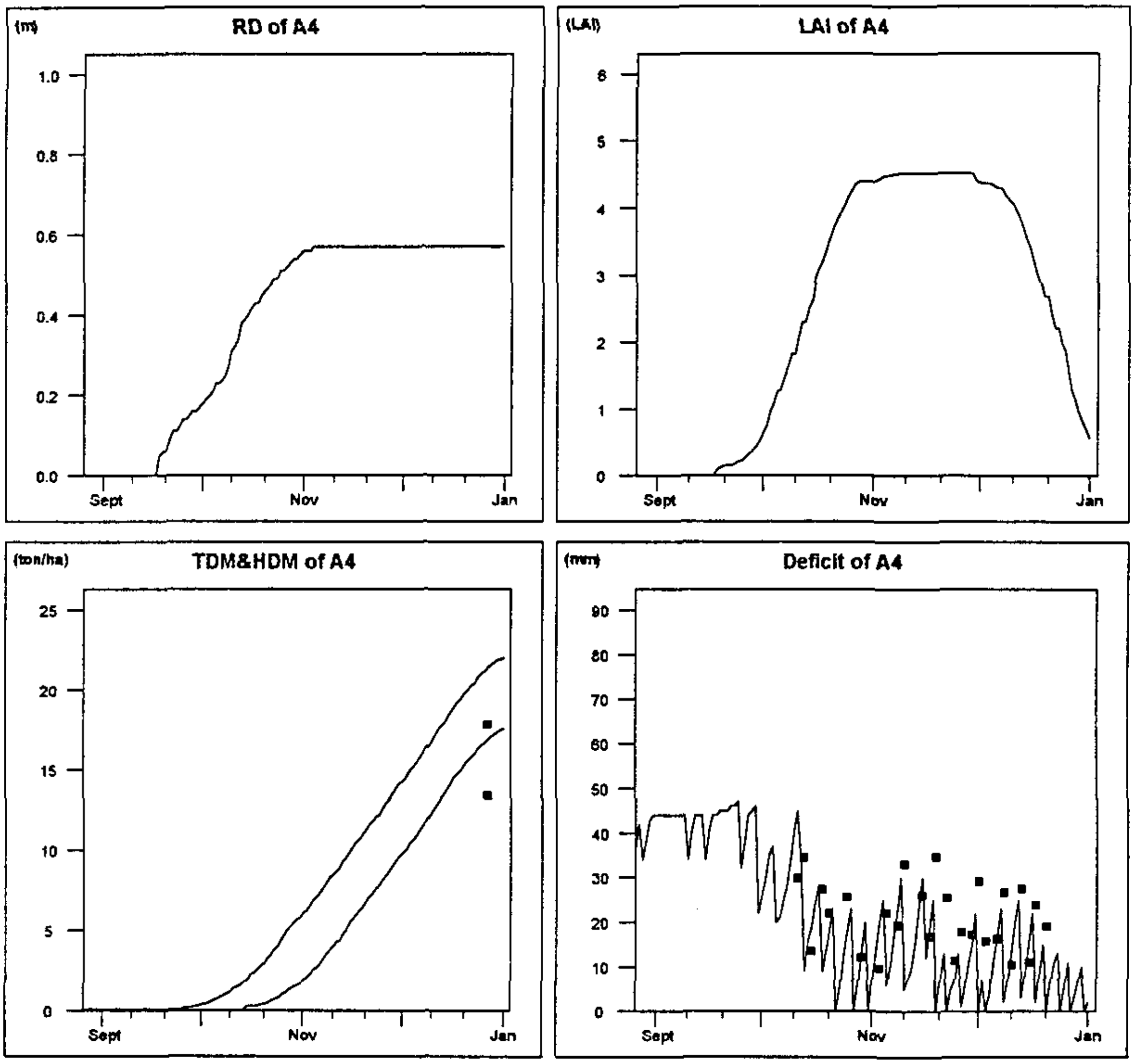


FIGURE 10.6 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm). Independent data set of an unstressed potato crop in the 1993 spring season after crop parameters were adapted

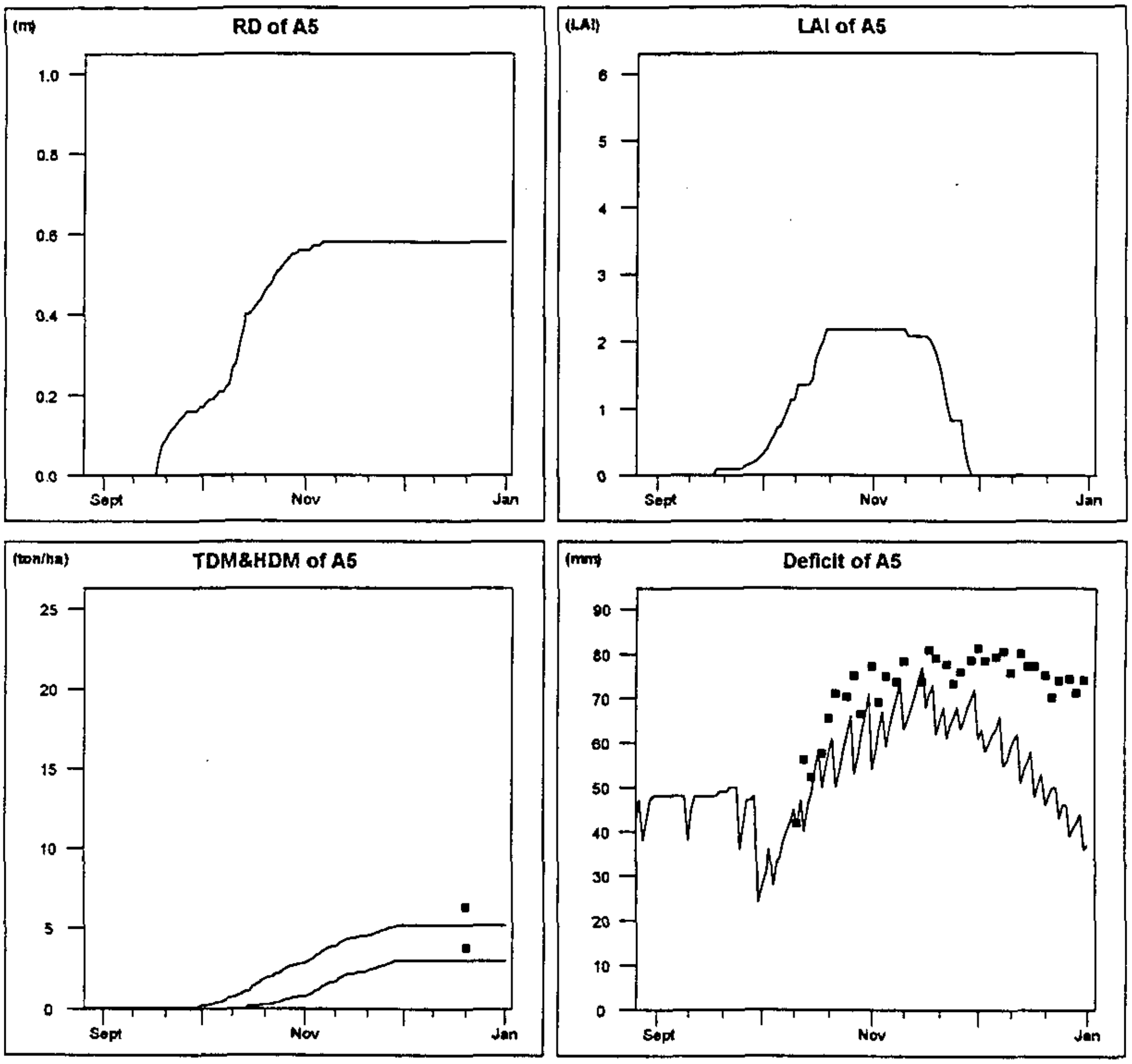
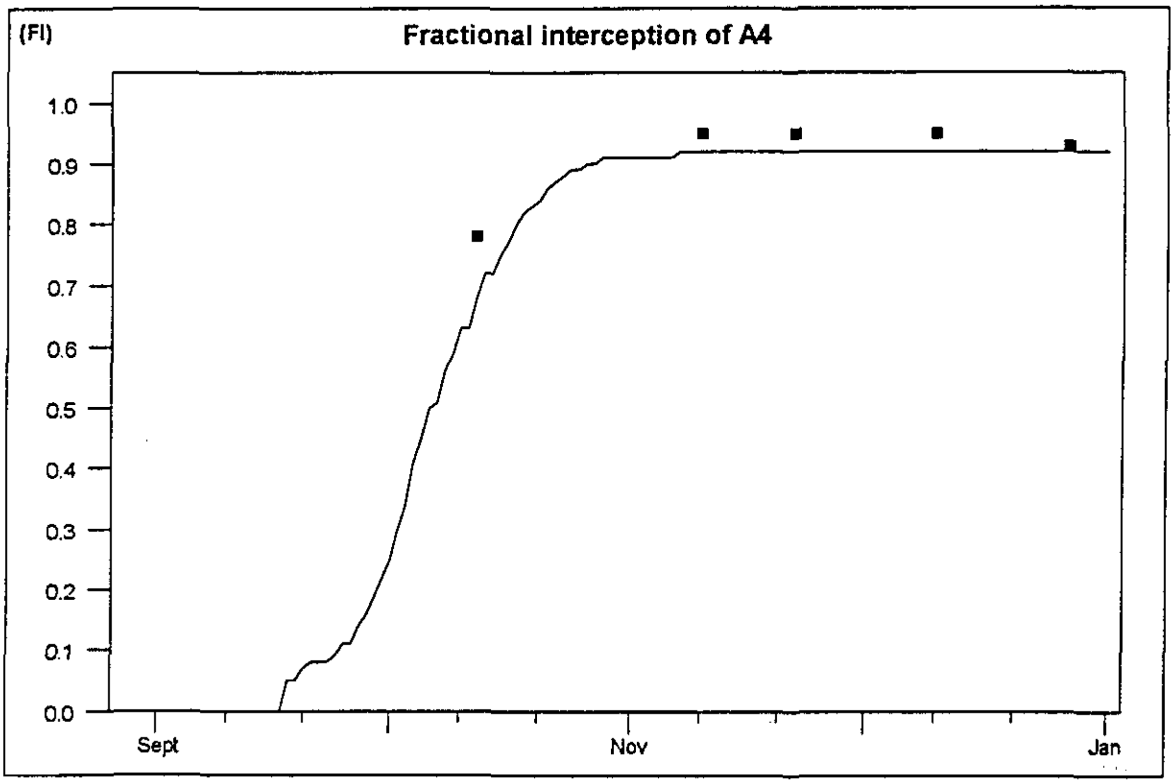


FIGURE 10.7 : Simulated (lines) and observed values (points) of rooting depth (RD, m), leaf-area index (LAI), harvestable dry matter (HDM, Mg ha^{-1}), total dry matter (TDM, Mg ha^{-1}) and soil-water deficit (mm). Independent data set of a water-stressed potato crop in the 1993 spring season after crop parameters were adapted



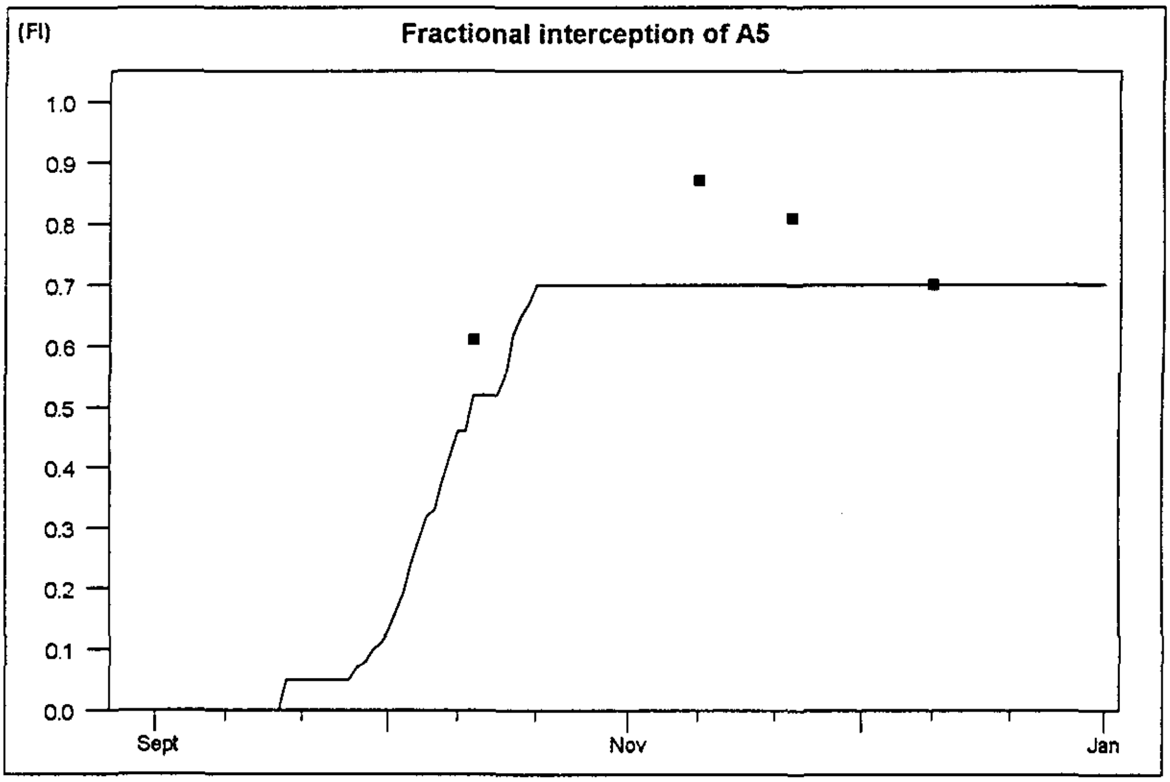


FIGURE 10.8 : Simulated (lines) and observed values (points) of fractional interception for independent data of an unstressed (top) and water-stressed (bottom) potato crop in the 1993 spring season after crop parameters were adapted

The five validation statistics proposed by De Jager (1994) were used to assess the accuracy of the SWB model when simulated soil-water deficits of the two water regimes were compared with measured values for the autumn 1992 planting. The statistical parameters compared include:

1. Slope through the origin (S)
2. Coefficient of determination (r^2)
3. Index of agreement of Willmot (1982) (D)
4. Root of the mean square error (RMSE)
5. Mean absolute error expressed as a percentage of the mean of the measured values (MAE)
6. The 80% accuracy frequency (D80)

Results of the model evaluations are given in Table 10.2. The last column lists the criteria set to be within an accuracy of 20%, a value recommended by Ritchie (1990) to be acceptable for simulation models. The accurate simulation of soil-water deficits for both water treatments was reflected by most of the parameters. This was also reflected by the plot of measured soil-water deficits against simulated values for both the unstressed and water-stressed conditions (Figure 10.9). For the water stressed treatment all the parameters were within the accuracy limits set in the last column of Table 10.2. The poor correlation between simulated and observed deficits during the last part of the growing season of the unstressed treatment, is reflected by the slope and 80% accuracy frequency values, which were slightly below the 20% reliability criterion.

The poor simulation of soil-water deficits late in the growing season of the unstressed crop should primarily be attributed to the incorrect simulation of canopy cover at that stage. Since the size of the canopy directly influences the rate of transpiration, water use will be simulated incorrectly when the canopy is senesced too early.

Table 10.2 : **Model evaluation of soil-water deficits simulated for potatoes subjected to two water treatments during the 1992 autumn planting. Statistical parameters used are the slope through the origin (S); coefficient of determination (r^2); index of agreement of Willmot (D); root of the mean square error (RMSE); mean absolute error expressed as a percentage of the mean of the measured values (MAE); the 80% accuracy frequency (D80) and the number of data points compared (n)**

Statistical parameter	Irrigation treatment		Reliability criteria
	Well-watered	Water stressed	
S	1.2	0.91	0.9 - 1.1
r^2	0.81	0.89	>0.8
D	0.91	0.97	>0.8
MAE (%)	15	9	<20
RMSE (mm)	4.33	4.49	-
D80 (%)	79	81	>80
n	28	27	

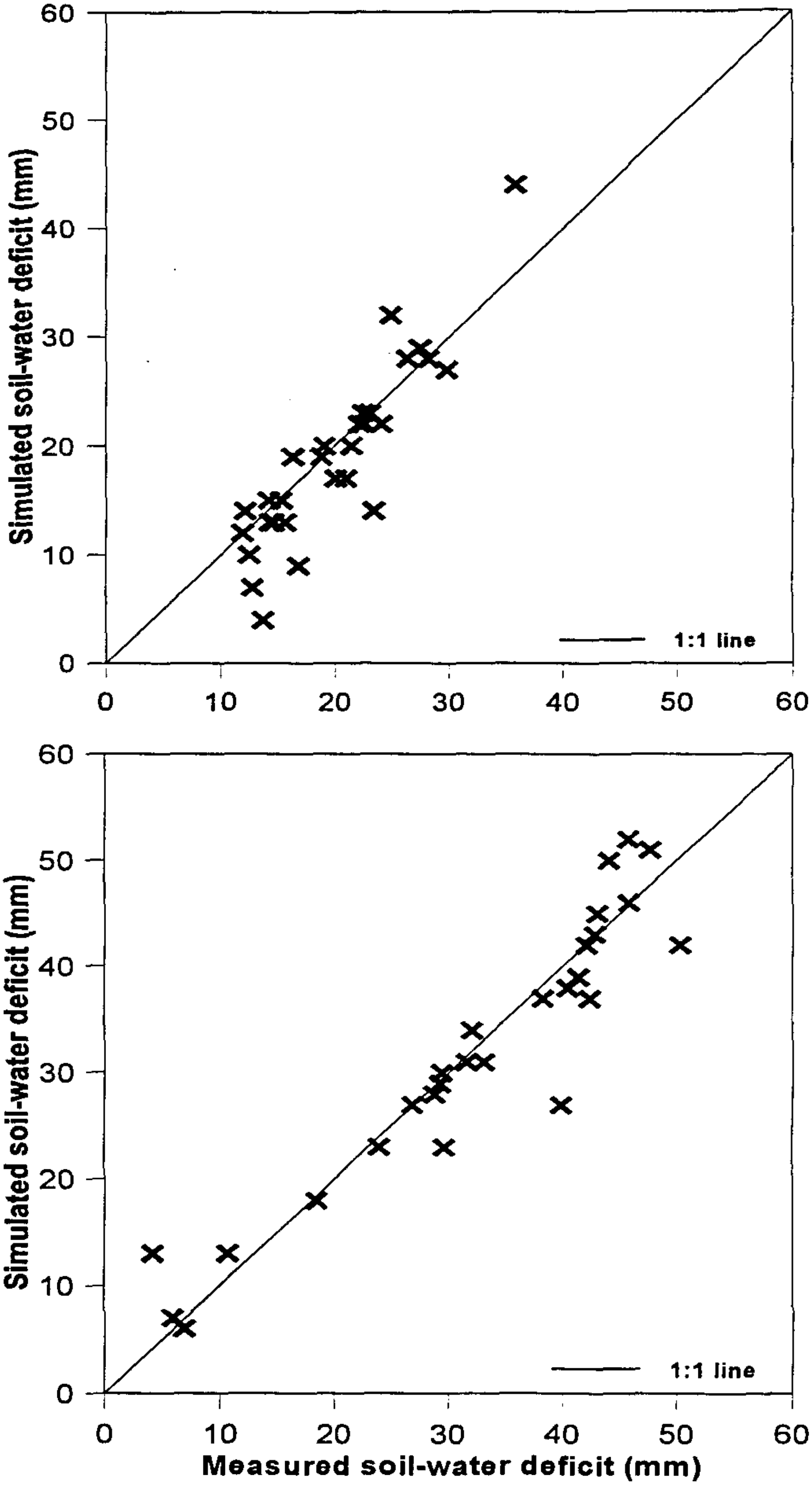


FIGURE 10.9: Simulated versus measured soil-water deficits recorded for potato crops under unstressed (top) and water-stressed (bottom) conditions for the 1992 autumn evaluation data set

10.5 Conclusions

The soil and atmospheric inputs required to run the Soil Water Balance (SWB) model are limited and easily obtainable, once the crop parameter file has been set up for the specific crop. Although the generic crop model is fairly simple, the soil-water balance was simulated to an acceptable level of accuracy for both well-watered and water-stressed autumn season potato crops. The date of crop senescence was, however, simulated too early and measured soil-water deficits at the end of the growing season were therefore generally higher than simulated values. Final tuber yield at harvest was also simulated reasonably well, but the level of accuracy obtainable with more mechanistic, crop-specific models should not be expected, as SWB is a generic crop model.

Simulations of crop growth and soil-water depletion were not accurate for spring plantings if the crop parameters determined for autumn plantings were used. Canopy size was underestimated and the estimated date of senescence was too early, resulting in incorrectly simulated soil-water deficits. This is probably because the generic crop model cannot simulate the effects of photoperiod and high temperatures on canopy development and assimilate distribution. After the thermal time requirements of different phenological stages were prolonged, simulations improved considerably, but for water-stressed conditions the canopy size, and therefore water use was underestimated.

The model should be a useful decision making tool for potato producers in helping them to decide when and how much to irrigate their crops on a daily basis. The latest Windows 95 version of the model also makes it extremely user friendly. Therefore, this tool will not only be accessible to extension personnel and advisors, but producers will be able to use it themselves.

Some aspects of the model that need to be addressed before final release include the following: (1) Determination of crop parameters for cultivars of different maturity classes. Since genotypes of the same maturity class showed only minor differences in water use within the same season (Chapter 7), there should be no necessity to determine parameters for each cultivar. (2) The inclusion of day length as a parameter to accommodate its effects on canopy development and date of maturity should improve the universal applicability of the model in different growing plantings (spring or autumn). As an alternative, separate crop parameters could be determined for spring or summer plantings.

CHAPTER 11

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The potato crop is well-known for its sensitivity to drought stress: yield and quality may be severely harmed by even mild water shortages at almost any growth stage of the crop. In South Africa, low annual rainfall and poor distribution of rain are major limiting factors for dry-land production of potatoes. Although about 73% of potato crops in this country are cultivated under intensive irrigation, plants are still often exposed to water- and heat stress due to the semi-arid climate.

The input costs of potato production are very high and producers are constantly seeking ways to reduce the risks in producing the crop. Regarding water use, two approaches could be followed to reduce the risks of yield and quality loss as a result of water stress: irrigation water could be used more efficiently and better adapted cultivars could be used.

As little is known about the water requirements of local potato genotypes, one objective of this study was to determine the amounts of water required by local potato genotypes for optimum production, as well as to determine the effects of water stress on tuber yield and quality.

Not all the genotypes could be included in the same trial because of limited space under the rain shelters where trials were conducted. Standard genotypes were therefore used in all the trials and the yields of genotypes were expressed relative the those of the standard genotypes. This method, although subject to some assumptions, enabled the comparison of genotypes over different years.

Genotypic yield differences in response to levels of water stress were mainly confined to the spring planting seasons, when temperatures and the atmospheric evaporative demand are higher than for autumn plantings. Some genotypes were clearly more adapted to water-stress conditions than others. Of the late genotypes Late Harvest and Mnandi performed best within the dry treatments, while Mnandi had the highest yields in the wetter treatments as well. Vanderplank, 82-252-5 and 83-252-1 had lower yields than most of the medium maturity class genotypes at the wet treatments, but had the highest yields when they were subjected to water stress. These findings challenge the suggestions of Jefferies & MacKerron (1993) that there is limited capacity for improved drought tolerance through breeding, other than improving potential yield: Late Harvest, Vanderplank, 82-252-1 and 83-252-1 had lower yield potentials than most of the genotypes they were compared with under favourable conditions, but had higher yields when they were stressed.

The ranking of genotypes according to yields attained at different water treatments is an important contribution to the current state of knowledge and will be valuable to producers in assisting them to select genotypes most suitable to their specific growing conditions. The ranking order of genotypes as a result of water treatments only changed for spring plantings, indicating that in autumn genotypes can be selected purely according to yield potential or specific needs of the end user. Another important implication of these findings is that, if producers have a choice between spring (or summer) and autumn (or winter) planting seasons, then there will be a larger range of high-yielding genotypes to select from for the cooler season. As yield differences between spring and autumn plantings were in most instances relatively small, high yields can usually be expected from autumn plantings, while the saving on irrigation water will be substantial.

In this study local potato genotypes were for the first time characterised according to drought tolerance and this objective was therefore fully met. Drought-tolerant genotypes were regarded as those that showed the lowest relative reduction in tuber yield when exposed to water stress. Mnandi, Late Harvest, Vanderplank, 82-252-5 and 83-252-1 were the most drought tolerant of the genotypes evaluated. Genotypic differences in drought tolerance were less pronounced in autumn, because temperatures and atmospheric evaporative demand were lower.

The drought-sensitivity index should be a valuable tool to plant breeders for the selection of drought-tolerant parental material in breeding programmes, but may be of less value to potato producers. A specific genotype, which is not classified as drought-tolerant, may because of a high yield potential, be ranked higher (according to yield) than a drought tolerant genotype, even in water-stress conditions. A typical example is Hoëvelder: this genotype is more drought- sensitive than Late Harvest as it shows greater yield reduction when exposed to water stress, but because of its high yield potential Hoëvelder will produce higher yields than Late Harvest under most conditions. A potato producer interested in a high yield will most probably select Hoëvelder, while a plant breeder will be more interested in Late Harvest as parental material in breeding programmes for drought tolerance.

The negative effect of water stress on tuber size was most severe in spring plantings, when temperatures and the atmospheric evaporative demand were higher. The yield of medium and especially large tubers were damaged by water stress, but genotypes did not respond differently to water stress within the same trial.

Water regimes apparently had less effect than temperature on tuber internal quality in spring plantings. Different water regimes had no effect on either tuber relative density or chip colour, presumably because of the negative effects of high temperatures on dry-matter and reducing-sugar content of the tubers. It appears that the application of more water to the wetter treatments did not cool the soil down sufficiently to compensate for the high ambient temperatures. According to Kincaid *et al.* (1993), the frequency of irrigation seems to be more important than the amount of irrigation in cooling the soil surface down. In the present study the frequency of irrigation was the same for all water treatments, because of the method of irrigation.

Chip colour was not affected negatively by water stress during autumn, as is often stated in the literature (Owings *et al.*, 1978; Kincaid *et al.*,1993; Shock *et al.*, 1993): chip colour generally improved with increase in stress levels for the genotypes studied. Low-temperature sweetening is suspected of being responsible for darker colours in the wet treatments: at the end of the tuber bulking phase minimum temperatures were usually lower than 10 °C, the temperature below which reducing sugars are reported to accumulate in tubers. Although not recorded, it can be assumed that soil temperatures were lowest for the wet treatments, as the soil surface was more completely covered by the larger crop canopies. Secondly, because wet soils have greater specific heat capacities they will heat up slower than dry soils, leading to lower temperatures (Trebejo & Midmore, 1990).

The objective to determine the effect of water regimes on tuber internal quality was only partly reached as, contrary to most reports in literature, water stress had no effect on tuber relative density and chip colour in spring plantings, while chip colour improved as a result of water stress in autumn. Firstly, the contradictory results are possibly attributable to the dominating effects of temperature on tuber quality. Secondly, the irrigation boom used does not resemble field conditions, due to the regular application of small amounts of water to dry treatments.

Although field screening methods, such as the technique used in this study, are preferred for the selection of drought-tolerant crops, the method is expensive, tedious, and the number of entries that can be included simultaneously is limited. From a breeder's point of view quick and reliable screening techniques that can be used on larger populations of early generation breeding material can be very useful. In this study photosynthetic rate (Pn) and stomatal resistance (Rs) were investigated as indicators of drought tolerance. Tuber yields correlated well ($r=0.87$ to $r=0.99$) with seasonal mean values of both these parameters for all the genotypes, but the regression functions that describe these relationships changed for plantings and genotypes. These variations are to be expected, as tuber yield is dependent on a number of physiological processes and Pn or Rs can at best only partly explain the final yields at harvest. The magnitude of decline in Pn or Rs in response to drought was, however, related to the magnitude of decline in tuber yield. These findings may be a significant contribution to early selection techniques for drought tolerance in crops.

The objective of finding suitable physiological parameters as early screening methods for drought tolerance in potatoes was reached, since the regression functions obtained from this study can in future be used to estimate the expected yield reduction of a specific genotype, once the reduction in Pn or increase in Rs for that genotype is established. Care should, however, be taken in the case of heat-sensitive genotypes such as Up-to-date, as the observed reduction in yield may be higher than the value estimated using the derived regression model.

Although these physiological measurements seem promising as methods for early screening of drought-tolerant material, they should be evaluated on independent data and on a wider range of more diverse material to prove their usefulness.

The vast differences in total water use between seasons and years were mainly as a result of differences in atmospheric evaporative demand. Normalising the water-use data for seasonal vapour pressure deficits narrowed the gap between years, but differences between spring and autumn plantings were still evident for the same genotypes. The reason for the remaining differences should probably be attributed to the fact that evapotranspiration and not transpiration data was used for comparisons.

The small differences observed between genotypes in water use can perhaps be explained by the way water use was calculated and by the method of irrigation used. Water use was mainly a function of water applied, as genotypes within the same maturity class received the same amount of water. Some of the genotypes might have been over- or under-irrigated in the process, and genotypic differences could only originate from differences in initial soil-water content or differences in soil-water depletion at the end of the growing season. Since genotypic differences in water use could not be determined with the irrigation technique used, this objective of the study was not reached. The irrigation boom is therefore not ideal for water use studies, although it is a valuable technique in screening for drought tolerance.

Water-use efficiencies were the highest for autumn plantings, because less water was lost through evaporation without contributing to the production of dry matter. The highest water-use efficiencies were generally recorded in the intermediate treatments (W2 and W3) for both plantings. The high-potential cultivars Up-to-date, BP1, Mnandi, 81-163-40 and Mondial had the highest efficiencies in autumn, independent of the water treatment applied, but in spring plantings the water-use efficiencies of genotypes were influenced by water treatments. Generally, Up-to-date, and 83-363-67 had the highest efficiencies in the wet to intermediate treatments, while the more drought-tolerant genotypes Vanderplank, Late Harvest and Mnandi had high efficiencies in all the water treatments in spring plantings. The medium-maturity genotypes 82-252-5 and 83-252-1 had the highest efficiencies in the driest treatments.

Rooting density in deep soil layers was not related to drought tolerance for the genotypes studied: both Mnandi and 83-252-1, two drought tolerant genotypes, had the lowest root densities throughout the entire soil profile, while Up-to-date, a drought-sensitive genotype had an abundance of roots, even at a soil depth of 1200 mm. These findings implicate that, although root distribution was slightly changed by water regime, root development is not a suitable indicator of drought tolerance in potato genotypes.

The Soil Water Balance model (SWB) was calibrated for the cultivar Up-to-date, using autumn planting data sets from earlier studies. SWB generally performed satisfactorily with regard to the simulation of dry matter production and water deficit of the soil profile for both well-watered and water-stressed conditions in autumn seasons. Simulations of crop growth and soil-water depletion were, however, not accurate in spring plantings if the crop parameters determined for autumn plantings were used. Canopy size was underestimated and the date of senescence was too early, resulting in incorrectly simulated soil-water deficits. The reason for the poor results in spring plantings is probably attributable to the fact that the effects of photoperiod and high temperatures on development and assimilate distribution is not taken into account by the generic crop model. The model therefore needs further refinement to ensure better simulations of canopy development over seasons, possibly by accommodating the effect of day-length on growth, development and senescence. Alternatively, separate crop parameters should be determined for spring or summer plantings.

Crop parameters should also be established for cultivars of other maturity classes, which will require complete growth analysis studies. The model should be a valuable irrigation scheduling tool to both advisors and potato producers.

Two of the objectives set for this study were not fully achieved. Firstly, the water requirements for optimal production of different genotypes did not differ within the same maturity class, possibly due to the equal amounts of water applied to all the genotypes in the same rain shelter. It is not known whether the calculated water use of genotypes would have been the same if different irrigation criteria had been adopted, another method of irrigation was used instead of the irrigation boom, or if measurements had allowed for quantification of drainage losses. Secondly, the effects of water stress imposed in different growth stages on growth and development, and therefore the identification of critical growth stages, could not be determined. The irrigation system used (boom) did not permit the imposition of different levels of water stress in different growth stages. A literature study was conducted to establish the current state of knowledge in this regard, which is discussed in Chapter 2.

Recommendations for future water-use studies on potatoes include the following: if the water requirements of individual genotypes are to be established, the irrigation boom system should deliberately not be used, for the reasons already elaborated in this section. These also apply to studies for determining the effect of water levels on tuber internal quality. The irrigation boom is, however, ideal when genotypes are to be screened for drought tolerance. The suitability of photosynthetic rate and stomatal resistance as early screening methods for drought tolerance should be evaluated on independent data sets before being applied. The SWB irrigation scheduling model should be refined to enable its use in any season. Crop parameters should also be established for potato cultivars of other maturity classes.

The technology transfer actions that have already taken place include the paper presentations, lectures and popular publications listed in Appendix A. This study forms the basis of a Ph.D. dissertation by the senior author and several scientific publications are to follow within the next year. A workshop is planned for the second half of 1997 in conjunction with the Potato Producers' Organisation. The purpose of the workshop will be to inform major role players in the potato industry on the most important research results and the conclusions drawn from the study. The SWB model calibrated as part of this study will also be demonstrated at the workshop.

LITERATURE CITED

ADAMS, S.S. & STEVENSON, W.R., 1990. Water management, disease development, and potato production. Potato management symposium papers. 67,3-11.

ANNANDALE, J.G. & STOCKLE, C.O., 1994. Fluctuation of evapotranspiration crop coefficients with climate: A sensitivity analysis. *Irrig. Sci.* 15, 1-7.

ANNANDALE, J.G., VAN DER WESTHUIZEN, A.J. & OLIVIER, F.C., 1996. Die fasilitering van tegnologie oordrag deur verbeterde besproeiingsriglyne vir groente en 'n meganistiese gewasmodeleringsbenadering. WNK Verslag No 476/1/96, Pretoria.

BANSAL, K.C. & NAGARAJAN, S., 1986. Leaf water content, stomatal conductance and proline accumulation in leaves of potato (*Solanum tuberosum* L.) in response to water stress. *Ind. J. Plant Physiol.* 29(4), 397-404.

BARRAGAN, J. & RECASENS, I., 1988. Irrigation experiment using a line-source sprinkler system. *Acta Hort.* 228, 83-89.

BENADE, N., ANNANDALE, J.G. & HESTER VAN ZIJL, 1996. The development of a computerized management system for irrigation schemes. WRC Report no 513/1/95.

BHAGSARI, A.S., WEBB, R.E., PHATAK, S.C. & JAWORSKI, C.A.,1988. Canopy photosynthesis, stomatal conductance and yield of *Solanum tuberosum* grown in a warm climate. *Am. Potato J.* 65, 393-407.

BODLAENDER, K.B.A., 1986. Effects of drought on water use, photosynthesis and transpiration of potatoes. 1. Drought resistance and water use. In: Potato Research of tomorrow. Eds. A.G.M. Beekman *et al.* Pudoc: Wageningen.

BOX, J.E. & RAMSEUR, E.L.. 1993. Minirhizotron wheat root data: Comparisons to soil core root data. *Agron. J.* 85, 1058-1060.

BRESLER, E., DAGAN, G., & HANKS, R.J., 1982. Statistical analysis of crop yield under controlled line-source irrigation. *Soil Sci. Soc. Am.J.* 46, 841-847.

BRISTOW, K.B. & CAMPBELL, G.S., 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agric. For. Meteor.* 31, 159-166.

BROWN, J., MACKAY, G.R., BAIN, H., GRITTITH, D.W. & ALLISON, M.J.,1990. The processing potential of tubers of the cultivated potato, *Solanum tuberosum* L., after storage at low temperatures. *Potato Res.* 33, 219-227.

BURGERS, M.S. & NEL, P.C., 1984. Potato irrigation scheduling and straw mulching. *S. Afr. J. Plant Soil.* 1(4), 111-116.

CALDIZ, D.O., 1991. Influence of origin and storage system on physiological age, crop growth and yield of seed potato. *Ind. J. Agric. Sci.* 61(1), 1-6.

CAMPBELL, G.S. & DIAZ, R., 1988. Simplified soil water balance model to predict crop transpiration. In: Drought research priorities. Eds. F.R. Bidinger & C. Johanson.

CAMPBELL, G.S. & STOCKLE, C.O., 1993. Prediction and simulation of water use in agricultural systems. In: International Crop Science. 1. CSSA, Madison.

CHAN, K.Y., & MEAD, J.A., 1992. Tillage-induced differences in the growth and distribution of wheat-roots. *Aust. J. Agric. Res.* 43, 19-28.

CEULEMANS, R., IMPENS, I., LAKER, M.C., VAN ASSCHE, F.M.G. & MOTTRAM, R., 1988. Net CO_2 exchange rate as a sensitive indicator of plant water status in corn (*Zea mays* L.). *Can. J. Sci.* 68, 597-606.

CHAUDHURI, U.N., DEATON, M.L., KANEMASU, E.T., WALL, G.W., MACRARIAN, V. & DOBRENZ, A.K., 1986. A procedure to select drought-tolerant sorghum and millet genotypes using canopy temperature and vapour pressure deficit. *Agron. J.* 78, 490-494.

COLEMAN, W.K., 1986. Water relations of the potato (*Solanum tuberosum* L.) cultivars Raritan and Shepody. *Am. Potato J.* 63, 263-276.

COLEMAN, W.K., TAI, G.C.C., CLAYTON, S., HOWIE, M. & PEREIRA, A., 1993. A portable monitor for the rapid assessment of processing quality of stored potato tubers. *Am. Potato J.* 70, 909-923.

COLES, G.D., LAMMERINK, J.P. & WALLACE, A.R., 1993. Estimating potato crisp colour variability using image analysis and a quick visual method. *Potato Res.* 36, 127-134.

COTHER, E.J., HOCKING, D. & LOGAN, B.J., 1981. Potato production in a semi-arid environment: agronomy, pathology and Riverina region of New South Wales, Australia. Technical Bulletin 25 Department of Agriculture, New South Wales. 1-36.

DE JAGER, J.M., 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA*. 20 (4), 307-314.

DEMAGANTE, A.L., HARRIS, P.M. & ZAAG, VAN DER, P.V, 1995. A promising method for drought tolerance in potato using apical cuttings. *Am. Potato J.* 72, 577-588.

DOGRAS, C., SIOMOS, A. & PSOMAKELIS, C., 1991. Sugar content and dry matter in potatoes stored under fluctuating temperatures in non-refrigerated stores in Greece. *Potato Res.* 34, 389-396.

DOORENBOS, J. & KASSAM, A.H., 1979. Yield response to water. FAO Irrigation and drainage paper 33. Rome.

DWELLE, R.B., KLEINKOPF, G.E. & PAVEK, J.J., 1981. Stomatal conductance and gross photosynthesis of potato (*Solanum tuberosum* L.) as influenced by irradiance, temperature and growth stage. *Potato Res.* 24, 49-59.

DWELLE, R.B., KLEINKOPF, G.E., STEINHORST, R.K., PAVEK, J.J. & HURLEY, P.J., 1981. The influence of physiological processes on tuber yield of potato clones (*Solanum tuberosum* L.): Stomatal diffusive resistance, stomatal conductance, gross photosynthetic rate, leaf canopy, tissue nutrient levels, and tuber enzyme activities. *Potato Res.* 24, 33-47.

DWELLE, R.B., 1985. Chapter 2. Photosynthesis and Photo assimilate Partitioning. In: Potato Physiology. Ed. P.H. Li. Academic Press Inc. Ltd. London.

EKANAYAKE, I.J., & MIDMORE, D.J., 1992. Genotypic variation for root pulling resistance in potato and its relationship with yield under water-deficit stress. *Euphytica.* 61, 43-53.

EWING, E.E., SENESAC, A.H. & SIECZKA, J.B., 1981. Effects of short periods of chilling and warming on potato sugar content and chipping quality. *Am. Potato J.* 58, 633-647.

EZEKIEL, R., PERUMAL, N.K. & SUKUMARAN, N.P., 1987. Diurnal changes in net photosynthetic rate of potato cultivars in the field. *Photosynthetica.* 21(4), 579-583.

EZEKIEL, R., PERUMAL, N.K. & SUKUMARAN, N.P., 1989. Stomatal density, stomatal resistance and photosynthetic rate in potato cultivars. *Photosynthetica* 23(4), 671-673.

FERNANDEZ, G.C.J., 1991. Repeated measure analysis of line-source sprinkler experiments. *Hort. Sci.* 26(4), 339-342.

FISCHER, R.A. & MAUER, R., 1978. Drought resistance in spring wheat cultivars. I. Grain yield response. *Austr. J. Agr. Res.* 29, 897-907.

FLETCHER, H.F.& MAURER, A.R., 1966. A movable rain shelter for small experimental plots. *Can. J. Plant Sci.* 46, 695-698.

FULTON, J.M., 1970. Relationship of root extension to the soil moisture level required for maximum yield of potatoes, tomatoes and corn. *Can. J. Soil Sci.* 50, 92-94.

GARROT, D.J., OTTMAN, M.J., FRANGMEIER, D.D. & HUSMAN, S.H., 1994. Quantifying wheat water stress with the crop water stress index to schedule irrigations. *Agron. J.* 86, 195-199.

GAWAD, A.A., OMER, E.A. & AHMED, S.S., 1990. Effect of storage on the glycoalkaloid and carbohydrate contents in different potato varieties. 23rd International Horticultural Congress. (27 Aug - 1 Sept. 1990) Firenze, Italy, 703-707.

GRAEME, D., COLES, J., LAMMERIK, P. & WALLACE, A.R., 1993. Estimating potato crisp colour variability using image analysis and a quick visual method. *Potato Res.* 36, 127-134.

GREEN, G.C., 1985. Estimated irrigation requirements of crops in South Africa. Memoirs on the agricultural natural resources of South Africa. No 1. Soil and Irrigation Research Institute. Dept. Agriculture and water supply, Pretoria.

HANKS, R.J., KELLER, J., RASMUSSEN, V.P. & WILSON, G.D., 1976. Division S-6-Soil and water management and conservation. *Soil Sci. Soc. Am. J.* 40, 426-429.

HANKS, R.J., SISSON, D.V., HURST, R.L. & HUBBARD, K.G., 1980. Statistical analysis of results from irrigation experiments using the line-source sprinkler system. *Soil Sci. Soc. Am. J.* 44, 886-888.

HARRIS, G.A., & CAMPBELL, G.S., 1989. Automated qualification of roots using a simple image analyser. *Agron. J.* 81, 935-938.

HARTZ, T.K. & MOORE, F.D., 1978. Prediction of potato yield using temperature and insolation data. *Am. Potato J.* 55, 431-436.

HARRIS, P.M., 1978. The Potato Crop. A scientific basis for improvement. London

HAVERKORT, A.J., VAN DER WAART, M. & BODLAENDER, K.B.A., 1990. The effect of early stress on numbers of tubers and stolons of potato in controlled and field conditions. *Potato Res.* 33, 89-96.

INCERTI, M. & O'LEARY, G.J., 1990. Rooting depth of wheat in the Victorian Mallee. *Austr. J. Exp. Agric.* 30, 817-824.

IRITANI, W.M. & WELLER, L.D., 1977. Changes in sucrose and reducing sugar contents of Kennebec and Russet Burbank tubers during growth and post-harvest holding temperatures. *Am. Potato J.* 54, 395-404.

IRITANI, W.M., 1981. Growth and preharvest stress and processing quality of potatoes. *Am. Potato J.* 58, 71-80.

JEFFERIES, R.A. & MACKERRON, D.K.L., 1987. Aspects of the physiological basis of cultivar differences in yield of potato under droughted and irrigated conditions. *Potato Res.* 30, 201-217.

JEFFERIES, R.A., 1989. Water-stress and leaf growth in field-grown crops of potato (*Solanum tuberosum* L.). *J. Exp. Bot.* 40 (221), 1375-1381.

JEFFERIES, R.A., HEILBRONN, T.D. & MACKERRON, D.K.L., 1989. Estimating tuber dry matter concentration from accumulated time and soil moisture. *Potato Res.* 32, 411-417.

JEFFERIES, R.A., 1993. Responses of potato genotypes to drought. I. Expansion of individual leaves and osmotic adjustment. *Ann. Appl. Biol.* 122, 93-104.

JEFFERIES, R.A. & MACKERRON, D.K.L., 1993. Responses of potato genotypes to drought. II. Leaf area index, growth and yield. *Ann. Appl. Biol.* 122, 105-112.

JEWELL, S., & STANLEY, R., 1989. The influence of defoliation date and harvest on the quality of potatoes for french fry production. *Potato Res.* 32, 431-438.

JOHNSON, K.B., CONLON, R.L., NELSON, D.C., ROUSE, D.I. & TENG, P.S., 1988. Validation of a simple potato growth model in the North Central United States. *Am. Potato J.* 65, 27-44.

KINCAID, D.C., WESTERMANN, D.T. & TROUT, T.J., 1993. Irrigation and soil temperature effects on Russet Burbank quality. *Am. Potato J.* 70, 711-722.

KOOMAN, P.L. & HAVERKORT, A.J., 1995. Modelling development of growth of the potato crop influenced by temperature and day length: LINTUL-POTATO. In: Potato Ecology and modelling of crops under conditions limiting growth. Eds. A.J. Haverkort & D.K.L. MacKerron. Kluwer Academic Publishers: Dordrecht.

KRUSE, E.G., ELLS, J.E. & McSAY, A.E., 1990. Scheduling irrigations for carrots. *Hort. Science*. 25(6), 641-644.

KVIEN, C.S., & BRANCH, W.D., 1988. Design and use of a fully automated portable rain shelter system. *Agron. J.* 80, 281-283

LARSEN, D.C., 1984. Simplifying potato irrigation scheduling - the Idaho program. *Am. Potato J.* 61, 215-227.

LEMAGA, B. & CAESAR, K., 1990. Relationships between numbers of main stems and yield components of potato (*Solanum tuberosum* L. cv. Erntestolz) as influenced by different daylenghts. *Potato Res.* 33, 257-267.

LESKOVAR, D.I. & CANTLIFFE, D.J., 1989. Pepper (*Capsicum annuum* L.) root growth and its relation to shoot growth in response to nitrogen. *J. Hort. Sci.* 64, 711-716.

LEVY, D., 1983a. Varietal differences in the response of potatoes to repeated short periods of water stress in hot climates. I. Turgor maintenance and stomatal behaviour. *Potato Res.* 26, 303-313.

LEVY, D., 1983b. Varietal differences in the response of potatoes to repeated short periods of water stress in hot climates. 2. Tuber yield and dry matter accumulation and other tuber properties. *Potato Res.* 26, 315-321.

LEVY, D., GENIZI, A. & GOLDMAN, A., 1990. Compatibility of potatoes to contrasting seasonal conditions, to high temperatures and to water deficit: The association with time of maturation and yield potential. *Potato Res.* 33, 325-334.

LOGAN, B.J., 1989. Effect of irrigation and nitrogen on yield and quality of potatoes grown in semi-arid South Western N.S.W. *Acta Hort.* 247, 243-24

LYNCH, D.R. & KOZUB, G.C., 1993. Effect of canopy size and shape on the tuber yield of sixteen potato genotypes. *Ann. appl. Biol.* 123, 93-103.

MACKERRON, D.K.L. & WAISTER, P.D., 1985. A simple model of potato growth and yield. *Agric. Forest. Meteor.* 34, 241-252.

MACKERRON, D.K.L. & JEFFERIES, R.A., 1988. The distributions of tuber sizes in droughted and irrigated crops of potato. I. Observations on the effect of water stress on graded yields from differing cultivars. *Potato Res.* 31, 269-278.

MACKERRON, D.K.L., 1989. Quantified responses of the potato crop to water-stress. Potato Research Symposium. Warmbaths, South Africa.. 1-5pp.

MAHALAKSHMI, V., BIDINGER, F.R. & RAO, G.D.P., 1990. Line-source vs. irrigated/nonirrigated treatments for evaluation of genotype drought response. *Agron. J.* 82, 841-844.

MARUTANI, M. & CRUZ, F., 1989. Influence of supplemental irrigation on development of potatoes in the tropics. *Hort. Science.* 24(6), 920-923.

MILLER, D.E. & MARTIN, M.W., 1987a. The effect of irrigation regime and subsoiling on yield and quality of three potato cultivars. *Am. Potato J.* 64, 17-25.

MILLER, D.E. & MARTIN, M.W., 1987b. Effect of declining or interrupted irrigation on yield and quality of three potato cultivars grown on sandy soil. *Am. Potato J.* 64, 109-117.

MILLER, D.E. & MARTIN, M.W., 1990. Responses of three early potato cultivars to subsoiling and irrigation regime on a sandy soil. *Am. Potato J.* 67, 769-777.

MOLL, A., 1983. Photosynthetic rate and yield of potato clones. *Potato Res.* 26, 191-202.

MOULD, R.D.& RUTHERFOORD, R.J., 1980. The effect of moisture stress during consecutive growth stages on tuber yield and quality of BP1 potatoes (*Solanum tuberosum* L.) *Crop Production*. 9, 89-95.

MUNNS, R. & PEARSON, C.P., 1974. Effect of water deficit on translocation of carbohydrate in *Solanum tuberosum*. *Austr. J. Pl. Physiol.* 1, 529-537.

NORTJE, P.F., 1988. The effects of soil moisture regimes on water use, yield and quality of cabbage and carrots. Ph.D. thesis, University of the Orange Free State, Bloemfontein.

OJALA, J.C., STARK, J.C. & KLEINKOPF, G.E., 1990. Influence of irrigation and nitrogen management on potato yield and quality. *Am. Potato J.* 67, 29-43.

OOSTERHUYS, D.M. & WALKER, S., 1987. Stomatal resistance measurement as an indicator of water deficit stress in wheat and soybeans. *S. Afr. J. Plant Soil.* 4(3), 113-120.

ORR, P.H. & JANARDAN, K.G., 1990. A procedure to correlate color measuring systems using potato chip samples. *Am. Potato J.* 67, 647-654.

OWINGS, T.R., IRITANI, W.M. & NAGEL, C.W., 1978. Respiration rates and sugar accumulation in normal and stressed Russet Burbank potatoes. *Am. Potato J.* 55, 211-220.

PENNYPACKER, B.W., LEATH, K.T., STOUT, W.L. & HILL, R.R., 1990. Technique for simulating field drought stress in the greenhouse. *Agron. J.* 82, 951-957.

PIETERSE, B.J., 1994. Fisiologiese veroudering van aartappelmoere. Ph.D. thesis. University of Pretoria, Pretoria.

POTATO PRODUCERS' ORGANISATION ANNUAL REPORT, 1995. PPO, Pretoria.

PRICE, M., JALALUDDIN, M.D. & DILDAY, R.H., 1992. Evaluation of rice germplasm for drought tolerance. As quoted by F.T. Rossouw and J. Waghmarae. *S. Afr. J. Sci.* 91, 149-150.

RICHARDSON, D.L., DAVIES, H.V. & ROSS, H.A., 1990a. An investigation into the factors influencing sugar levels in UK grown potatoes (cv. Record). *Potato Res.* 33, 235-239.

RICHARDSON, D.L., DAVIES, H.V. & ROSS, H.A., 1990b. Potato tuber sugar content during development and storage (10 °C): possible predictors of storage potential and the role of sucrose in storage hexose accumulation. *Potato Res.* 33, 241-245.

ROBINSON, J.M. & HUBBARD, K.G., 1990. Soil water assessment model for several crops in the high plains. *Agron. J.* 82, 1141-1148.

ROSSOUW, F.T. & WAGHMARAE, J., 1995. The effect of drought on growth and yield of two South African potato cultivars. *S. Afr. J. Sci.* 91, 149-150.

RUTHERFOORD, R.J. & DE JAGER, J.M., 1975. Water status and stomatal behaviour of BP1 potatoes (*Solanum tuberosum* L.) and their effect upon yield. *Crop Production.* 4, 125-128.

SCANLON, M.G., ROLLER, R., MAZZA, G. & PRITCHARD, M.K., 1994. Computerized video image analysis to quantify color of potato chips. *Am. Potato J.* 71, 717-733.

SCHAPENDONK, A.H.C.M., SPITTERS, C.J.T.& GROOT, P.J., 1989. Effects of water stress on photosynthesis and chlorophyll fluorescence of five potato cultivars. *Potato Res.* 32, 17-32.

SHIMSHI, D., SHALHEVET, J. & MEIR, T, 1983. Irrigation regime effects on some physiological responses of potato. *Agron. J.* 75, 262-268.

SHOCK, C.C., HOLMES, Z.A., STIEBER, T.D., ELDREDGE, E.P. & ZHANG, P., 1993. The effect of timed water stress on quality, total solids and reducing sugar content of potatoes. *Am. Potato J.* 70, 227-241.

SINGH, M., RAO, R.C.N. & WILLIAMS, J.H., 1991, A statistical assessment of genotypic sensitivity of groundnut (*Arachis hypogae* L.) to drought in line source sprinkler experiments. *Euphytica.* 57, 19-25.

SMITH, M., 1992. Expert consultation on revision of FAO methodologies for crop water requirements. FAO Report, Rome.

SOWOKINOS, J., 1990. Effect of stress and senescence on carbon partitioning in stored potatoes. *Am. Potato J.* 67, 849-857.

SPITTERS, C.J.T., NEELE, A.E.F. & SCHAPENDONK, A.H.C.M., 1988. Crop physiological components of tuber yield and their use in potato breeding. As quoted by R.A. Jefferies and D.K.L. MacKerron. *Ann. Appl. Biol.* 122, 105-112.

SPITTERS, C.J.T. & SCHAPENDONK, A.H.C.M., 1990. Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. *Plant Soil.* 123, 193-203.

STALHAM, M.A & ALLEN, E.J., 1993. Effect of irrigation regime on rooting density of contrasting cultivars. Abstracts of the 12th Triennial Conference of the EAPR. 186-187pp. Paris, France.

STARK, J.C., 1987, Stomatal behaviour of potatoes under nonlimiting soil water conditions. *Am. Potato J.*, 64, 301-309.

STEYN, J.M., DU PLESSIS, H.F. & NORTJE, P.F., 1992. Die invloed van verskillende waterregimes op Up-to-date aartappels. II. Opbrengs, grootteverspreiding, kwaliteit en waterverbruik. *S. Afr. J. Plant Soil.* 9(3), 118-122.

STRUIK, P.C. & VAN VOORST, G., 1986, Effects of drought on the initiation, yield, and size distribution of tubers of *Solanum tuberosum* L. cv. Brintje. *Potato Res.* 29, 487-500.

SUKUMARAN, N.P., EZEKIEL, R. & PERUMAL, N.K., 1989. Response of net photosynthetic rate and stomatal conductance to water deficit in different potato cultivars. *Photosynthetica.* 23(4), 664-666.

SUSNOSCHI, M. & SHIMSHI, D., 1985. Growth and yield studies of potato development in a semi-arid region. 2. Effect of water stress and amounts of nitrogen top dressing on growth of several cultivars. *Potato Res.* 28, 161-176.

TAN, C.S. & FULTON, J.M., 1985. Water uptake and root distribution by corn and tomato at different depths. *Hort Science.* 20(4), 686-688.

TANNER, C.B., 1981. Transpiration efficiency of potato. *Agron. J.* 73, 59-64.

TANNER, C.B., & SINCLAIR, T.R., 1993. Efficient water use in crop production: Research or re-search? In: Limitations to efficient water use in crop production. Eds. H.M. Taylor, W.R. Jordan & T.R. Sinclair. SSSA Publication, Madison, USA.

TREBEJO, I., & MIDMORE, D.J., 1990. Effect of water stress on potato growth, yield and water use in a hot and cool tropical climate. *J. Agric. Sci.* 114, 321-334.

UPCHURCH, D.R., RITCHIE, J.T. & FOALE, M.A., 1983. Design of a large dual-structure rainout shelter. *Agron. J.* 75, 845-848.

VAN DER MESCHT, A., DE RONDE, J.A. & ROSSOUW, F.T., 1992. Specific DNA binding of a 38 kDa polypeptyde during drought stress in potato. *J. S. Afr. Soc. Hort. Sci.* 2, 92-95.

VAN LOON, C.D., 1981. The effect of water stress on potato growth, development and yield. *Am. Potato J.* 58, 51-69.

VAN LOON, C.D., 1986. Drought, a major constraint to potato production and possibilities for screening for drought resistance. In: Potato research of tomorrow. Eds. A.G.B. Beekman *et al.* Proceedings of International Seminar, Wageningen, Netherlands, Pudoc: Wageningen.

VAN HEEMST, D.J., 1986. The distribution of dry matter during growth of a potato crop. *Potato Res.* 29, 55-66.

VOS, J. & GROENWOLD, J., 1988. Water relations of potato leaves. I. Diurnal changes, gradients in the canopy, and effects of leaf-insertion number, cultivar and drought. *Annals of Botany.* 62, 363-371.

VOS, J. & GROENWOLD, J., 1989. Characteristics of photosynthesis and conductance of potato canopies and the effects of cultivar and transient drought. *Field Crops Res.* 20, 237-250.

WILCOX, D.A. & ASHLEY, R.A., 1982. The potential use of plant physiological responses to water stress as an indication of varietal sensitivity to drought in four potato (*Solanum tuberosum* L.) varieties. *Am. Potato J.* 59, 533-545.

WILCOX-LEE, D., 1990. Effect of soil on growth, water relations and photosynthesis in an open-pollinated and male hybrid asparagus cultivar. *Acta Hort.* 271, 457-465.

WILLMOT, C.J., 1982. Some comment on the evaluation of model performance. *Bull. of Am. Meteorol. Soc.* 64, 1309-1313

WOLF, S., OLESKINSKI, A.A., RUDICH, J. & MARANI, A., 1990. Effect of high temperature on photosynthesis in potatoes. *Annals of Botany.* 65, 179-185.

WOLF, S., 1993. Effect of leaf on photosynthesis, carbon transport and carbon allocation in potato plants. *Potato Res.* 36, 253-262.

YAU, S.K., 1995. Regression and AMMI analyses of genotype X environment interactions: An empirical comparison. *Agron. J.* 87, 121-126.

ZELITCH, I., 1975. Improving the efficiency of photosynthesis. *Science.* 188, 626-633.

APPENDIX A

TECHNOLOGY TRANSFER ACTIONS THAT EMANATED FROM THE RESEARCH PROJECT:

1. Papers presented at scientific conferences:

STEYN, J.M. & DU PLESSIS, H.F., 1993. 'n Evaluasie van die droogteverdraagsaamheid van Suid-Afrikaanse aartappelcultivars. SA Society for Crop Production (SASCP) Congress. Rustenburg, South Africa.

DU PLESSIS, H.F. & STEYN, J.M., 1993. Fotosintesetempo van aartappelcultivars soos beïnvloed deur tekortbesproeiing. SASCP Congress. Rustenburg, South Africa.

STEYN, J.M. & DU PLESSIS, H.F., 1993. Evaluation of the drought resistance of three potato cultivars in South Africa. European Association for Potato Research (EAPR) Triennial Conference. Paris, France.

STEYN, J.M. & DU PLESSIS, H.F., 1996. Production, water use and drought tolerance of two new potato genotypes. SASCP Congress. Bloemfontein, South Africa. (The D.F. Retief trophy for the best paper by a young scientist was presented to the senior author for this paper).

STEYN, J.M. & ANNANDALE J.G., 1996. Soil Water Balance: A generic model suitable for the irrigation scheduling of potatoes. EAPR Triennial Conference. Veldhoven, The Netherlands.

STEYN, J.M. & ANNANDALE J.G., 1997. Irrigation scheduling of potatoes using the Soil Water Balance model. First All Africa Crop Science Congress, Pretoria.

2. Poster presented at scientific conferences:

STEYN, J.M. & DU PLESSIS, H.F., 1994. An evaluation technique for drought tolerance in potatoes. SASCP Congress. Cedara, South Africa.

3. Popular publications:

STEYN, J.M., 1993. Doeltreffende watervoorsiening kan aartappelopbrengste verdubbel. Roodeplaat Bulletin 38, 6-7.

MARTIN STEYN & HENNIE DU PLESSIS, 1995. Nuwe cultivars presteer in droogte. Roodeplaat Bulletin 41, 18.

FLIP STEYN & MARTIN STEYN, 1995. Die effek van waterstremming op die aartappelplant. Chips, 9, 3, 27.

MARTIN STEYN, HENNIE DU PLESSIS & PIERRE FOURIE, 1995. Nuwe cultivars presteer in droogte. Chips, 9, 4, 39.

4. Lectures presented on courses and information days:

STEYN, J.M., 1993. Waterbehoeftes en besproeiingskedulering van aartappels. Potato Short Course. Citrusdal, South Africa.

STEYN, J.M., 1995. Waterbehoeftes van aartappels. Information day. Louwna, South Africa.

STEYN, J.M., 1996. Die verbouing, water- en voedingsbehoeftes van aartappels. Potato cultivation course. Tolwe, South Africa.

STEYN, J.M., 1996. The cultivation and irrigation of potatoes. Vegetable Course. Roodeplaat, South Africa.

5. Radio talks

MARTIN STEYN, 1996. Besproeiingskedulering en modellering van aartappels - report on a visit to the Cambridge University, United Kingdom.

6. Post-graduate studies

STEYN, J.M., 1997 (D.V.). Response of potato genotypes to different water regimes. Ph.D. Thesis, University of Pretoria.

APPENDIX B

TABLE B1: Summary of ANOVA table for AMMI: The influence of different water regimes on tuber yield of six potato genotypes during the 1992 autumn planting

Source	df	Mean sum of squares	Probability level	
Treatment	29	647.64	0.0000	***
Genotype	5	255.25	0.0000	***
Water	4	4289.43	0.0000	***
Genotype X water	20	17.38	0.8694	NS
IPCA 1	8	30.38	0.3552	NS
Residual	12	8.71	0.9836	NS
Error	90	27.04		
Total	119	178.28		

TABLE B2: **Marketable tuber yield (Mg ha^{-1}) of late-maturity potato genotypes as influenced by different water regimes and plantings**

Year	Planting	Genotype name	Water regime				
			W1	W2	W3	W4	W5
1992	Spring	Vanderplank	46.0	41.1	31.1	19.6	9.0
		Up-to-date	53.4	59.3	32.9	15.3	3.4
		Late Harvest	47.4	46.6	38.3	28.0	9.8
1993	Autumn	Vanderplank	42.2	41.9	28.1	22.1	11.2
		Up-to-date	54.2	49.5	39.4	31.6	15.3
		Late Harvest	53.6	52.1	43.1	32.7	16.9
1993	Spring	Late Harvest	53.0	42.5	37.3	26.7	8.8
		Hoëvelder	63.4	54.4	38.0	28.0	6.8
		Mnandi	66.3	64.6	47.2	34.5	12.0
1994	Autumn	Late Harvest	56.2	44.8	41.2	26.6	17.0
		Hoëvelder	56.1	43.9	36.4	25.8	16.9
		Mnandi	66.4	49.1	42.0	28.6	16.2
1994	Spring	Late Harvest	49.4	51.2	44.0	34.0	13.1
		81-163-40	57.7	48.5	47.5	30.5	3.6
		83-363-67	59.9	58.1	46.4	33.5	8.4
1995	Autumn	Late Harvest	31.3	26.9	21.9	20.1	17.1
		81-163-40	37.4	30.1	26.2	23.3	18.9
		83-363-67	30.5	23.7	20.5	17.8	13.2

TABLE B3: Marketable tuber yield (Mg ha^{-1}) of medium-maturity potato genotypes as influenced by different water regimes and plantings

Year	Planting	Genotype name	Water regime				
			W1	W2	W3	W4	W5
1992	Spring	Vanderplank	46.1	44.8	41.1	28.0	15.9
		Up-to-date	63.6	65.5	54.3	29.5	9.1
		Late Harvest	54.8	53.7	45.5	31.7	12.0
1993	Autumn	Vanderplank	27.4	24.6	27.0	21.6	14.1
		Up-to-date	60.4	59.3	49.1	41.8	31.8
		Late Harvest	53.6	51.3	47.3	36.7	28.3
1993	Spring	Up-to-date	67.1	68.5	51.0	18.9	7.7
		82-252-5	55.2	48.0	35.1	26.8	9.1
		83-252-1	58.1	52.0	36.5	24.8	10.1
1994	Autumn	Up-to-date	50.9	46.1	44.7	41.0	26.7
		82-252-5	53.0	49.0	53.7	45.9	26.4
		83-252-1	47.4	43.6	45.5	43.7	23.1
1994	Spring	Up-to-date	72.1	59.9	42.4	24.5	5.0
		Mondial	67.5	58.6	39.8	21.7	6.1
		84-304-4	44.7	38.9	33.0	20.6	7.7
1995	Autumn	Up-to-date	28.7	24.7	19.4	17.3	17.7
		Mondial	41.9	37.5	29.3	24.5	20.9
		84-304-4	24.9	25.3	19.8	15.8	13.8

TABLE B4: **Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different late-maturity potato genotypes during the 1992 - 1994 spring plantings**

Source	df	Mean sum of squares	Probability level *	
Treatment	29	0.2793	0.0000	***
Genotype	5	0.5726	0.0000	***
Water	4	0.7319	0.0000	***
Genotype X water	20	0.1155	0.0357	*
IPCA 1	8	0.1900	0.0063	**
Residual	12	0.0658	0.4155	NS
Error	59	0.0625		
Total	88	0.1339		

* NS : not significant

TABLE B5: **Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different late-maturity potato genotypes during the 1993 - 1995 autumn plantings**

Source	df	Mean sum of squares	Probability level	
Treatment	29	0.0672	0.0014	**
Genotype	5	0.3282	0.0000	***
Water	4	0.0334	0.3046	NS
Genotype X water	20	0.0087	0.9966	NS
IPCA 1	8	0.0144	0.8276	NS
Residual	12	0.0049	0.9987	NS
Error	60	0.0270		
Total	89	0.0401		

TABLE B6: **Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different medium-maturity potato genotypes during the 1992 - 1994 spring plantings**

Source	df	Mean sum of squares	Probability level *	
Treatment	24	0.6832	0.1683	NS
Genotype	4	0.2390	0.7485	NS
Water	4	2.9363	0.0006	***
Genotype X water	16	0.2310	0.9519	NS
IPCA 1	7	0.4999	0.4366	NS
Residual	9	0.0218	0.9999	NS
Error	49	0.4954		
Total	73	0.5572		

* NS : not significant

TABLE B7: **Summary of ANOVA table for AMMI: The influence of water regimes on relative tuber yield of different medium-maturity potato genotypes during the 1993 - 1995 autumn plantings**

Source	df	Mean sum of squares	Probability level	
Treatment	29	0.2658	0.0000	***
Genotype	5	1.4197	0.0000	***
Water	4	0.0922	0.0019	**
Genotype X water	20	0.0120	0.8755	NS
IPCA 1	8	0.0233	0.3047	NS
Residual	12	0.0045	0.9956	NS
Error	60	0.0192		
Total	89	0.0995		