UNIVERSITY OF SOUTHERN QUEENSLAND

PARTIAL ROOTZONE DRYING AND DEFICIT IRRIGATION IN COTTON FOR USE UNDER LARGE MOBILE IRRIGATION MACHINES

A dissertation submitted by

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ABSTRACT

There is currently a shortage of irrigation water available for cotton production in Australia due to recent climatic and legislative conditions. Some growers have responded to this water shortage by changing from traditional furrow irrigation to alternative irrigation systems such as centre pivots and lateral move irrigations (collectively known as large mobile irrigation machines – LMIMs). Improved efficiency of irrigation application, as well as labour savings, have been the main reasons for the increased adoption of LMIMs. The use of LMIMs also enables a higher level of control in water application in terms of irrigation volume, timing and placement. As a result, growers now have much greater control over soil moisture conditions which enables the implementation of improved irrigation management strategies that have the potential for improved crop water use productivity (yield/ML).

Two irrigation strategies which have been demonstrated to achieve benefits in terms of crop water use are partial rootzone drying (PRD) and deficit irrigation (DI). PRD and DI involve manipulating the placement of irrigation water and the moisture deficit maintained in the root zone, respectively. Neither PRD nor DI is able to be applied easily under furrow irrigation. However, both PRD and DI may be able to be implemented under LMIMs within the Australian cotton industry. Deficit irrigation has been shown to be effective at improving water use productivity in cotton, although it is not widely used within the Australian cotton industry. Similarly, there has been little research conducted to identify whether cotton responds to partial rootzone drying and there is currently little understanding of the way in which DI and PRD strategies could be implemented commercially using LMIMs.

This research carried out from 2002 to 2005 investigated the response of cotton to a range of PRD and deficit irrigation strategies for use under LMIMs. Assessment of the biochemical and physiological response of cotton to PRD and regulated deficit irrigation strategies was conducted under glasshouse conditions in Toowoomba, Qld.

Field trials conducted under a commercial centre pivot and lateral move situated on the Darling Downs assessed the crop response, soil moisture movement, yield and gross production water use associated with the implementation of a range of PRD and deficit treatments. Modelling of rainfall probability and soil moisture movement were also undertaken to quantify constraints to the successful commercial implementation of irrigation management strategies such as PRD within the Australian cotton industry.

PRD applied to cotton grown in split-pot containers under glasshouse conditions was found to produce a biochemical response in the form of a four fold increase in xylem Abscisic Acid concentration. The application of alternated PRD strategies was generally found to reduce both vegetative (i.e. height, leaf area) and reproductive (i.e. fruiting sites) plant growth compared to Control treatments irrigated on both sides of the plant. Increasing the period between PRD alternations from 5 to 15 days when the soil moisture potential in the wet root zone was maintained between 30 and 60 kPa also reduced the plant height and the number of fruiting sites. However, where the soil moisture in the wetted root zone was maintained at <3 kPa and alternation was based on the dry root zone moisture levels 16% (~350 kPa) and 10% (>1500 kPa) there was no difference in the major plant growth indicators (i.e. height, fruiting branches, fruiting sites, leaf area) between the various alternated PRD treatments. This suggests that the level of moisture availability in the wet root zone area is a key factor influencing water uptake and crop stress under alternated PRD conditions.

No significant difference in crop growth or yield was found as a result of the PRD treatments implemented under commercial field conditions. However, this may have been attributed to the inability to apply and maintain a sufficient soil moisture gradient across the root zone to successfully induce biochemical signalling from PRD. Practical limitations in the successful application of PRD in cotton production are attributed to the soil hydraulic properties, current irrigation practices (i.e. volume and frequency of water applied) and the occurrence of in-season rainfall events.

Rainfall probability and soil moisture modelling were used to evaluate the practical application of PRD within the Australian cotton industry. This work suggested that the creation of a soil moisture gradient across the plant root zone large enough to trigger a PRD response is most likely to be achieved on light textured soils located in semi-arid regions which experience minimal in-season rainfall events. However, the conditions are only met for a relatively small proportion of the current Australian cotton industry. Hence, it would seem that further research into the benefits of implementing PRD in cotton under LMIMs is not warranted.

Regulated deficit irrigation applied under glasshouse conditions was found to have a controlling influence over partitioning between vegetative and reproductive growth. Improved physiological and gross production to water use benefits were measured as a result of deficit irrigation under field conditions and regulated deficit irrigation under glasshouse conditions. Deficit irrigation (79% of predicted ET) under field conditions produced a 31.5% improvement in gross production water use index (GPWUI = Yield / Total water applied (rainfall, irrigation and stored soil moisture)) over commercial practice (i.e. applying 100% of predicted ET). However, the largest benefits derived from deficit irrigation were associated with the management of crop agronomics (i.e. vegetative growth, retention rate and crop earliness) and the increased ability for capture of in-crop rainfall. Hence, deficit irrigation may provide substantial benefits for the cotton industry in terms of productivity of irrigation water applied as well as total water applied (irrigation, rainfall and soil moisture reserves).

The ability to implement a suitable deficit irrigation strategy is regionally and seasonally dependent as the uncertainty over the timing of rainfall events and irrigation allocation both within and between seasons makes the optimal use of water resources difficult. Hence, future research should aim to enhance current crop production models to predict crop growth and response to a range of deficit irrigation treatments. Greater knowledge and adoption in the use of climatic predictors (such as SOI) are required to improve the volume and timing of deficit irrigations applied. An economics framework should be developed which encompasses resource costs and constraints on a farm basis to enable the identification of optimal management practices based on the risk profiles of the various deficit irrigation strategies. Irrigation scheduling under LMIMs is also currently limited by the use of point scale soil moisture measurements (especially under low energy precision applicator (LEPA) socks) and this may be improved by the use of plant based sensors.

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own efforts and/or were conducted under my supervision, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any award, except where otherwise acknowledged.

Signature of Candidate	Date

ENDORSEMENT

Signature of Supervisor/s	Date

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ABA	Abscisic Acid
[ABA]	Concentration of Abscisic Acid
CWU	Crop Water Use (Plant Mass / Water applied)
CWUI	Crop Water Use Index (Yield / Evapotranspiration)
DAP	Days After Planting
DAT	Days After Transplant
DATI	Days After Trial Initiation
DI	Deficit Irrigation
IE	Irrigation Efficiency
ELISA	Enzyme Linked Immunosorbent Assay
GPWUI	Gross Production Water Use Index (Yield / Total water applied- including; rainfall, irrigation and stored soil moisture)
$IWUI_{FG}$	Irrigation Water Use Index $_{Farm\ Gate}$ (Yield / Irrigation water supplied to farm gate)
$IWUI_{Applied}$	Irrigation Water Use Index $_{Applied}$ (Yield / Irrigation water applied to the field)
LAI	Leaf Area Index
LEPA	Low Energy Precision Applicator
LMIM	Large Mobile Irrigation Machines
NMM	Neutron Moisture Meter
PLC	Programmable Logic Controller
PRD	Partial Rootzone Drying
RDI	Regulated Deficit Irrigation
WUE	Water Use Efficiency
Ψ_l	Leaf Water Potential
Ψ_s	Stem Water Potential
g_s	Stomatal Conductance

PUBLICATIONS ARISING FROM THIS RESEARCH

White S.C. & Raine S.R. (2004). Identifying the potential to apply deficit irrigation strategies in cotton using large mobile irrigation machines. *Proceedings 4th International Crop Science Congress*, 26 Sept–1 Oct, Brisbane. Australia.

White, S.C. (2004). Regulated deficit irrigation and partial rootzone drying. In "WaterPAK: a guide for irrigation management in cotton". Cotton Research and Development Corporation, Narrabri.

White, S.C. & Raine, S.R. (200X). Physiological responses of cotton to a root zone soil moisture gradient imposed using split-pots. *Plant and Soil* (submitted 1st September 2006)

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1.0 INTRODUCTION

Australia's farming sector is under increasing pressure to improve water use productivity (Yield/ML) as a result of recent drought, environmental concerns regarding sustainable river ecosystems and government policies on water metering and allocations. Cotton is a major user of irrigation water in Australia. An estimated 1526 GL of irrigation water was used for cotton production during the 2002/2003 cropping season, representing 15% of the total water diverted for irrigation purposes in Australia (ABS, 2005). In recent years, irrigation water has become the most limiting resource for cotton production. Under these circumstances, maximising agronomic water use productivity may be more profitable to the farmer than maximising crop yield (Pereira, Oweis & Zairi 2002).

Over 90% of irrigated cotton in Australia is currently grown under furrow irrigation (Foley & Raine 2001). However, there has recently been a rapid increase in the adoption of large mobile irrigation machines (LMIMs) such as centre pivots and lateral moves for cotton production. It was estimated that 4% of the Australian cotton crop was irrigated with LMIMs in 2001, but this proportion is predicted to increase to more than 30% by 2020 (Foley & Raine 2001). The recent adoption is due to the improvements achievable in irrigation water use index ($IWUI_{FG}$) and crop water use index (CWUI) achievable with LMIMs compared to furrow irrigation. $IWUI_{FG}$ is defined as the proportion of irrigation water supplied to the farm gate which is eventually made available to be used by the crop (rootzone soil moisture), and CWUI is the yield produced per unit of water evaporated and transpired during the growing season (Milroy & Tennakoon 2002, Purcell & Currey 2003).

Increased $IWUI_{FG}$ with LMIMs is achieved by reductions in distribution and application losses on farm compared to furrow. CWUI improvements result from the ability to maintain more desirable soil moisture conditions for crop growth during the season improving yield and/or reducing water use.

It is agronomically desirable to maintain the soil moisture at a mild deficit for cotton production (Hearn & Constable 1984). A mild soil moisture deficit provides adequate water for crop transpiration while limiting the potential for excessive vegetative growth. However, severe soil drying can cause plant stress, limiting both the photosynthetic capacity and assimilate production required for crop development and high yield. It is difficult to maintain a mild soil moisture deficit using furrow irrigation on the heavy clay soils common to the Australian cotton industry. Yield losses due to waterlogging after irrigation commonly occur with furrow irrigation (Hodgson & Chan 1982, Thongbai et al. 2001) and significant soil drying often occurs between irrigation events.

Centre pivots and lateral move machines are able to apply smaller and more frequent irrigations than furrow. This improves soil water management and provides the ability to target agronomically desirable soil moisture conditions. Deficit irrigation (DI) and partial rootzone drying (PRD) are management strategies that have been successfully used in other crops to improve CWUI. These strategies require the ability to control both the amount and placement of irrigation water to maintain a desired soil moisture deficit for all or part of the crop growing season. PRD differs from DI by simultaneously maintaining both a wet and a drying portion of the root zone where as DI strategies create a level of moisture deficit throughout the root zone. However, there is currently little data on the benefits and limitations of DI and PRD in cotton, nor guidelines on the ability to implement these strategies for cotton production in Australia.

DI has been found to produce an increase in water use productivity for a variety of crops (Hutmacher *et al.* 1994, Kang, Shi & Zhang 2000, Kirda 1999, Marsal *et al.* 2002, Mitchell & Shennan 1991, Mpelasoka, Behboudian & Mills 2001, Torrecillas *et al.* 2000). Similarly, Yazar, Sezen & Sesversen (2002) found no significant difference in cotton yields when deficit irrigated at 50 to 100% of cumulative Class-A-pan evaporation. However, few commercial cotton growers in Australia use DI strategies and there has been no research conducted locally on the benefits and limitations associated with the implementation of DI under LMIMs.

PRD aims to improve crop water use by exploiting the plant's biochemical signals which regulate stomatal behaviour without changing shoot water potential (Davies, 2002). The benefits of PRD have been evaluated in a wide range of crops including grapes, olives, citrus fruits, peaches, pears, tomatoes, aubergines, raspberries and maize (Chalmers & Kirstic 2001, Davies *et al.* 2000, Dry *et al.* 1996, Dry *et al.* 2000, Kang *et al.* 1998, Kang *et al.* 2000, Kriedemann & Goodwin 2003, Loveys *et al.* 1997, Loveys, Stoll & Dry 2001, Loveys *et al.* 1998, Sobeith *et al.* 2004, Stoll, Loveys & Dry 2000, Topcu *et al.* 2002). PRD has been most successful in grapes with claims of improvements in water use ranging from 86-90% (Kriedemann & Goodwin 2003). Topcu, Kirda et al (2002) have recently conducted a preliminary evaluation of PRD in cotton.

The increasing adoption of LMIMs within the Australian cotton industry provides an opportunity to implement PRD and DI strategies. However, the benefits of utilising these strategies and the practicality in implementation are unknown. Hence, there is a need to better understand the crop's biochemical, physiological and yield responses to these irrigation strategies as well as identify the practical limitations to the successful commercial application of PRD and/or DI under local conditions. Therefore, the aim of this research was to evaluate the benefits of, and practical limitations to, the implementation of PRD and DI strategies under large mobile irrigation machines in the Australian cotton industry.

Chapter 2 of this dissertation provides a review of the relevant literature regarding PRD and DI in cotton and other crops. This leads to the identification of knowledge gaps and the development of the specific objectives for this research program. The research activities included glasshouse trials (Chapter 3) to identify the biochemical and physiological responses of cotton to PRD and regulated DI and a series of field evaluations (Chapter 4) of PRD and DI strategies under LMIMs. An industry analysis of the climatic and soil conditions affecting the potential to impose PRD commercially was also undertaken (Chapter 5). The main outcomes from this work conducted and the implications for the cotton industry and further research opportunities are also discussed in Chapter 6.

2.0 LITERATURE REVIEW

This chapter provides an overview of the existing literature in relation to irrigation of cotton and the potential to utilise deficit irrigation (DI) and partial rootzone drying (PRD) strategies to improve crop water use productivity. The physiological responses of cotton to soil-water management and the current irrigation application practices in the Australian cotton industry are outlined in section 2.1. Section 2.2 is a review of the biochemical and physiological processes involved in deficit irrigation and partial rootzone drying. Cotton specific PRD and DI research and industry specific issues regarding the commercial application of these strategies under field conditions are reviewed in Section 2.3. The specific research objectives arising from this review are outlined in Section 2.4.

2.1 Soil-water and Irrigation Management in the Australian Cotton Industry

2.1.1 Physiological Responses of Cotton to Soil-Water Management

Optimum irrigation management involves the choice of a cost effective, efficient water delivery system, as well as a thorough knowledge of the sensitivity of crop growth and yield to temporal changes in root zone water availability (Hutmacher *et al.* 1994). Before investigation into alternative irrigation methods for improved water use productivity can be discussed, it is prudent to understand the physiology of cotton and its response to various levels of soil moisture deficit.

2.1.1.1 Growth of Cotton Plants

The morphological development of cotton follows an orderly and regular pattern (Hearn 1994). Cotton development is indeterminate, in that the main stem never terminates in an inflorescence but is capable of producing a new node every 2 to 4 days depending on temperature (Eaton 1955, Hearn & Constable 1984). Cotton growth can be broadly divided into vegetative and reproductive growth. Only vegetative growth occurs during early plant development, with the main priority being to develop leaf area for plant photosynthesis and assimilate production. Reproductive growth is initiated when the first fruiting branch appears, usually between the 5th and 8th main stem node (Hearn 1994). Fruiting sites precede the fruiting branches at regular intervals along the fruiting branches. Due to the indeterminacy in growth habit, vegetative and reproductive processes occur together once the first fruiting branch is produced. This means there is no morphological limit to either the number of fruiting sites initiated or to yield and that the rate of plant growth and yield is limited by plant (e.g. crop canopy age) and environmental (e.g. water, nutrition, light and temperature) factors (Hearn & Constable 1984).

2.1.1.2 Nutritional Theory of Shedding and Cutout

Shedding and cut out are important characteristics of cotton growth and development. The numbers of fruit which are retained and matured per plant is determined by the plant's supply of photosynthates. As cotton plants develop, the number of fruit and their demand for assimilates initially increases exponentially, while assimilate supply increases asymptotically due to leaf area and canopy age (Hearn 1994). Eventually growth, flowering, and boll retention decrease when the demand for photosynthates increases and exceeds the supply (Eaton 1955, Guinn

1985). This pronounced decrease in growth due to the limited supply of photosynthate is referred to as cutout (Paterson et al., 1978 cited in Guinn (1985).

Unlike the reduction in main stem growth which occurs due to cutout, development of individual fruit does not slow down (Hearn 1994). The plant aborts (i.e. sheds) a number of fruit to maintain the nutritional supply to the remaining maturing fruit. If physiological stress (e.g. limited soil moisture) occurs, then fruit shedding will increase to maintain the development of the reduced number of maturing fruit. This process of the plant balancing assimilate demand and supply by shedding fruiting structures is termed the nutritional theory of shedding. In the presence of limited nutritional supply, assimilate preference is given to more mature bolls over younger bolls which are shed (Turner *et al.* 1986).

As cotton is grown in an annual cropping system, the maximum achievable yield must be produced within the available season window. Cotton, in common with some other plants, initiates two to three times more fruiting sites than it can mature and therefore cotton's indeterminacy confers compensatory fruit development (Constable 1991). Excessive fruit loss will occur in the presence of a physiological stress which limits photosynthesis and therefore assimilate supply. However, once the stress is lifted the and assimilate supply increased, compensation through the retention of alternative fruit which may have otherwise been lost occurs. Excessive stress and fruit drop may therefore not limit yield but will cause a delay in crop yield.

Cotton plants maintain a balance between the supply of carbohydrate produced through photosynthesis and the demand for carbohydrates from plant structures (e.g. stem, leaves, roots, and fruiting structures). The greater the in-season variation in requirements (e.g. light, water, temperature, nutrition) for photosynthesis and growth, the less efficiently the plant can accommodate a given level of stress and the longer it takes for the plant to recover. Cutout before the end of the growing season due to plant stress and limited photosynthetic supply will cause reduced yields. However, cutout at the end of the season is desirable and can be used as a management tool to define crop maturity and reduce carbon wastage from maturing bolls which will not be picked (Hearn 1994). It also serves to deprive insect pests of a food source before they enter diapause (Guinn 1985).

Soil water availability is one of the primary edaphic factors which act to influence, and perhaps even control, production of potential fruiting points, retention of squares and bolls, and yield of cotton (Jordan 1986). Understanding the interaction of the plant with the soil-water supply and the aerial environment dictating water use is essential to proper water management (Krieg 2000). Hence, to achieve optimum yield and water use productivity requires a well-managed irrigation system and an understanding of cotton responses to soil moisture conditions.

2.1.1.3 Crop Stress and Soil Moisture Deficit

Cotton, like most other plants, must maintain a balance between the water supply stored in the soil system and the atmospheric evaporative demand in order to carry out sustained growth and the development processes necessary for productivity and economic yield (Krieg 2000). Hence, the soil-plant-atmosphere continuum should be considered as a dynamic system for determining appropriate irrigation schedules (Anadranistakis *et al.* 2000).

Evapotranspiration (ET) is water vapour loss from a crop to the atmosphere and is the sum of evaporation (E) from the soil surface and transpiration (T) through the plant (Hearn 1994). The water demand of cotton varies throughout the season due to changes in leaf area (transpirational surface) and prevailing environmental conditions affecting the rate of evaporation. The rate of evapotranspiration is determined primarily by meteorological factors, canopy development and the response of the crop to water deficit as the water supply is depleted (Hearn 1994). Crop yield and plant water use productivity in water-limited environments can be improved by increasing the ratio of dry matter or yield per plant to water loss or transpiration per plant (Gerik, Landivar & Faver 1994). To achieve this, knowledge of the plant response to given soil moisture deficits must be known.

The range of soil moisture levels encountered by plants can range from saturation (e.g. soil moisture content is above field capacity and "waterlogged") down to permanent wilting point when no more soil moisture is able to be extracted by the plant. Soil moisture deficits occur when the soil moisture content is depleted below field capacity or the drained upper limit as a result of ET. Plant stress occurs when a soil moisture deficit exists to an extent that causes a change in the rate of physiological processes. Depending on the period and extent of the stress, this may result in a reduction in the economic returns from the crop by reducing crop yield or quality.

Cotton is well adapted to survival in conditions of variable soil moisture deficit and is able to alter almost all plant functions in response to imposed levels of soil moisture deficit (Hearn 1994). Cotton initially responds to a moisture deficit by reducing its rate of ET to conserve water. At high levels of moisture deficit, cotton plants ensure survival through increased reproductive activity.

When soil moisture is readily available (near field capacity or the upper limit of plant available water) vegetative growth is maximised and reproductive growth is either avoided or reduced through facultative shedding of fruiting structures. The response of cotton to wet conditions by facultative shedding is the major contributor to the occurrences of excessive vegetative growth (i.e. rank growth). Rank growth is characterised by shedding of fruit, long internodes, and excessive plant height and leaf area (Hearn 1994).

As water supply becomes limited, cotton responds by slowing expansive or vegetative growth and increasing reproductive growth by retaining and maturing fruiting structures (Turner *et al.* 1986). Vegetative growth eventually terminates as young fruit are shed and old fruit are matured (Figure 2.1). In this way cotton plants ensure survival through increased reproductive activity.

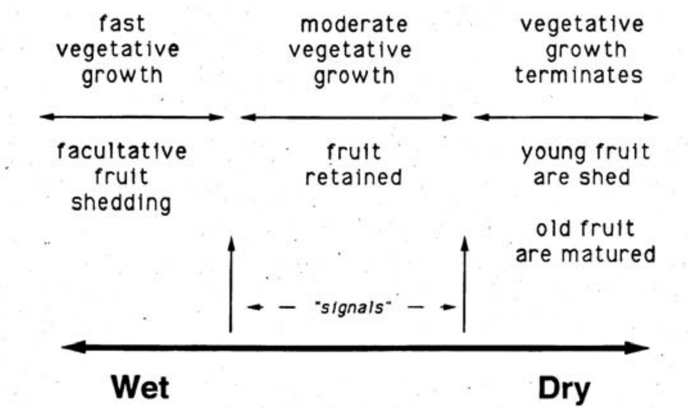


Figure 2.1 Specific adaptive responses of cotton to the environmental water regime (Hearn 1994)

The growth response of cotton to soil moisture is important in managing the crop to attain a desirable balance between vegetative and reproductive growth. The adaptive response of cotton to water confers reproductive flexibility in response to the variable and unpredictable water supply (Hearn 1994). In more complex terms, cotton responses to increasing soil moisture deficit can be described in terms of a hierarchy of effects.

2.1.1.4 Hierarchy of Soil-Water Responses

Soil moisture deficits impose a range of physiological impacts on cotton growth and yields (Figure 2.2). Various researchers, e.g. (Ball, Oosterhuis & Mauromoustakos 1994, Ephrath, Marani & Bravdo 1990, Hearn 1994, Turner *et al.* 1986) have identified a hierarchy of effects on cotton growth due to soil water deficits.

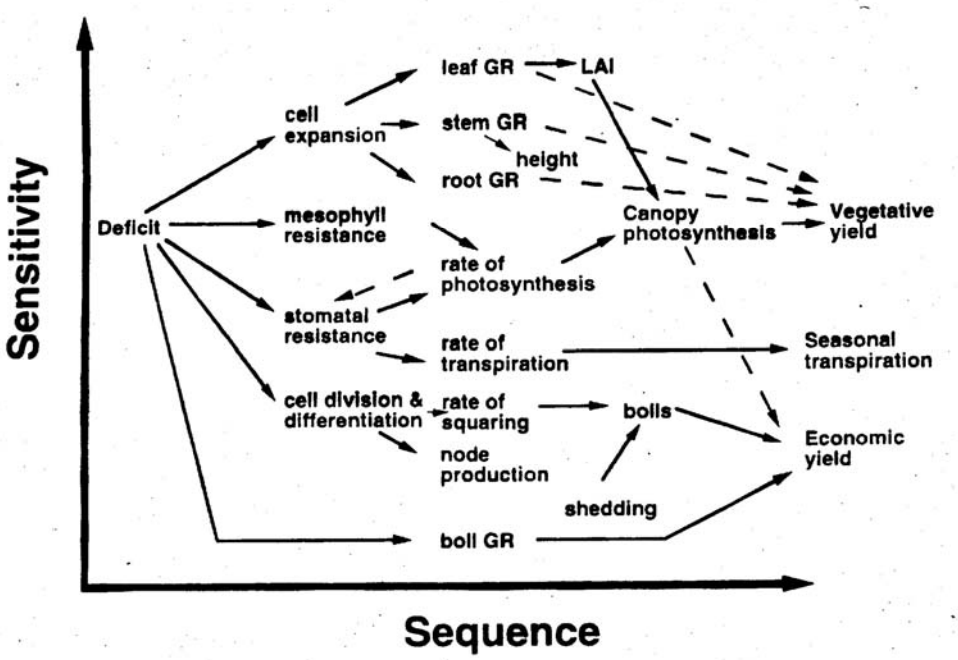


Figure 2.2 Hierarchy of effects on cotton from water stress (Hearn 1994)

Cell expansion is the first process to be affected by water deficits. This reduction in cell expansion affects leaf, stem and root growth, but does not directly affect the photosynthetic rate (Hearn 1994, Turner *et al.* 1986). Hence, decreases in economic yield associated with mild water deficits are primarily due to a reduction in canopy size and corresponding photosynthetic capacity of the plant. Where higher deficits are imposed, the rate of photosynthesis and therefore assimilate production is reduced. This directly leads to a reduction in cell division and differentiation affecting the rate of boll production and yield.

Maturing bolls already present have been found to have an advantage over vegetative organs when water deficits are applied. Bolls are supplied most of their water through the phloem and are not dependent on water potential gradients (Hearn 1994). This enables them to maintain water potential and turgor during periods of mild water deficit. Under a mild moisture stress, increased photo-assimilates can be made available for reproductive development due to the reduced transpiration stream to, and growth rate of, vegetative leaf growth. This confers a nutritional priority on bolls and gives them a competitive advantage for assimilates over vegetative growth when under a mild deficit (Hearn 1994). The differential response of vegetative and reproductive growth in cotton to a mild moisture deficit can have a profound effect on crop performance and therefore has important agronomic implications.

2.1.1.5 Agronomic Implications for Soil Water Management

Under conditions of low soil-water deficit, the cotton plant maximises vegetative growth and agronomically excessive leaf production can occur (Milroy, Goyne & Larsen 2002). Increases in leaf area can increase crop water use by increasing the transpirational area and crop water demand, increasing difficulty in spray penetration and efficacy, increasing shading on lower fruiting structures (leading to increased potential for boll rot and fruit shedding) and reducing fertiliser use efficiency. Agronomic manipulation of the rate of cotton boll setting can be achieved by water management which lowers water input and reduces the occurrence of excessive vegetative growth (Hearn 1975).

Vegetative growth can be controlled while not significantly reducing photosynthetic rate by manipulating water inputs to maintain a mild moisture deficit (Figure 2.3). This results in bolls having priority for assimilates, greater fruit retention and promotion of earlier fruit development. Creating an earlier boll load increases the earliness of the crop. It may also produce an entomological advantage as less chemically resistant insect pests are present early in the season compared with increasing resistance to chemicals applied to late season insect populations

(Constable & Gleeson 1977). However, this may become less of an issue with the advent of genetically modified cotton varieties (e.g. bollgard).

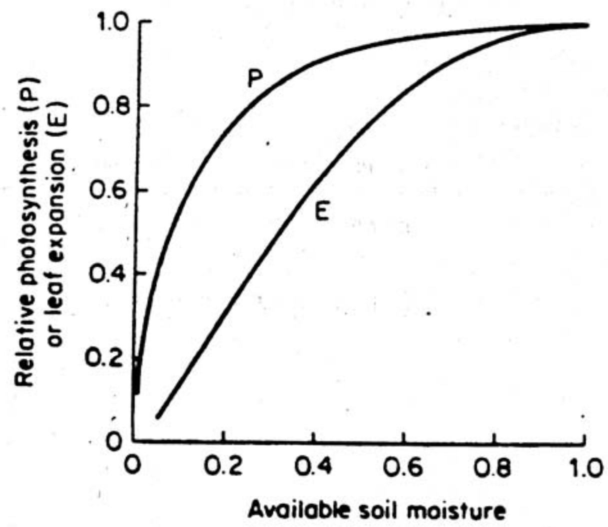


Figure 2.3 Relationship between available soil water and relative leaf net photosynthesis (P) and relative daily leaf expansion (E) (Constable, 1982 cited in (Turner et al. 1986)

It is agronomically desirable to maintain soil moisture at a mild deficit which minimises excessive vegetative growth while still maintaining photosynthesis and maximising the amount of surplus assimilate from vegetative growth for boll development (Hearn & Constable 1984). Maintaining a mild moisture deficit should also minimise both the occurrence of water logging due to rain after an irrigation event and drought stress from excessive soil moisture deficits. Hence, irrigation strategies in cotton which maintain a mild soil moisture deficit and reduce the amplitude change in soil moisture should improve commercial water use productivity.

2.1.2 Irrigation Practices in the Australian Cotton Industry

Approximately 90% of the annual cotton crop grown in the semi-arid climate of eastern Australia requires supplementary irrigation (Hearn 1994). Of this area, over

90% is furrow irrigated. Hence, most of the existing recommendations for irrigation management in the cotton industry are based on the management of furrow irrigation systems. However, the use of large mobile irrigation machines (LMIMs) and drip systems is predicted to increase dramatically over the next 20 years (Foley & Raine 2001). This is mainly due to the improvements in water and labour efficiency achievable with these systems.

Typical industry practice on traditional cotton growing clay soils involves an irrigation prior to sowing (i.e. pre-irrigation) or immediately after planting. Subsequent irrigations are applied at a target soil moisture deficit of approximately 50% of the plant available water-holding capacity (Milroy, Goyne & Larsen 2002). Furrow irrigation is generally ceased once approximately 20% of bolls are open (Milroy, Goyne & Larsen 2002).

The large fluctuations in soil moisture associated with furrow irrigation often make it difficult to maintain soil moisture within a desirable mild deficit range. Furrow irrigation practices generally saturate the soil surface and complete refill the soil moisture profile. This minimises soil moisture deficit for a period of time and increases the potential for waterlogging. Yield losses of up to 9, 19, 16 and 4 kg/ha/day have been found due to waterlogging during squaring, peak flowering, late flowering and boll maturation, respectively (Milroy, Goyne & Larsen 2002). However, the period between furrow irrigations is often too long under high ET conditions resulting in significant moisture stress which may lead to a reduction in photosynthetic rate and the crop cutting out early.

The irrigation system employed has a major influence on the efficiency and uniformity of the water application. Centre pivots and lateral move machines generally have a higher uniformity of application and application efficiency than furrow irrigation (Foley & Raine 2001). However, LMIMs using sprinklers wet the entire soil and plant surfaces potentially resulting in a proportion of the applied water to be lost to evaporation (Krieg 2000). Hence, irrigation practices which reduce the area of plant and soil surface wet during an irrigation event will reduce evaporative losses and enable a greater proportion of irrigation water applied to be made available to the plant.

Low energy precision applicator (LEPA) socks (Plate 2.1) were developed by Lyle and Bordovsky (1981) to maximise the utilisation of seasonal rainfall and increase irrigation efficiencies by reducing sprinkler irrigation losses associated with evaporation and droplet drift in high winds (Yazar, Sezen & Sesveren 2002). Irrigation with LEPA socks minimises plant and soil surface wetting by delivering the irrigation water to the soil surface, normally between every second plant row. This eliminates evaporation of water droplets either discharging from a sprinkler nozzle or on the plant surface, and minimises soil surface evaporation.

Plate 2.1 LEPA sock used under centre pivots and lateral moving irrigators to apply irrigation water to the soil surface between crop rows

Considerable savings in water use are achievable with a centre pivot or lateral move machine fitted with LEPA socks over standard furrow irrigation. LMIMs fitted with LEPA socks have been found to have an application efficiency (water available to the crop in the rootzone / water applied to the field) greater than 90% (Krieg 2000). However, the irrigation management strategy employed under these machines can also play a vital role in the success of the irrigation system in terms of water use productivity. The current adoption of centre pivots and lateral moves in the Australian cotton industry has been limited by the use of management practices more consistent with surface irrigation strategies (Foley & Raine 2001, Raine, Foley & Henkel 2000). Few growers are currently obtaining the benefits of irrigation flexibility associated with varying the quantity and frequency of irrigation water applied. There are also currently few industry guidelines regarding the irrigation of cotton with LMIMs or drip systems.

2.2 Deficit Irrigation and Partial Rootzone Drying

Two irrigation strategies which have been shown to increase the water use productivity of various crops are deficit irrigation (DI) and partial rootzone drying (PRD). Both DI and PRD are irrigation management techniques which limit water availability to improve water use productivity. The key difference between the two strategies is that DI limits water availability over time, where as with PRD the irrigation water is manipulated over space (Kriedemann & Goodwin 2003). To obtain a net benefit from PRD or DI, any yield or other harvestable characteristic which may be negatively impacted by the imposed soil moisture deficit needs to be outweighed by the benefits of earlier crop maturity, increased water use productivity and/or other harvest characteristics improved by the implementation of the strategies.

2.2.1 Deficit Irrigation (DI)

Cotton acclimatises to repeated root zone water deficits by exhibiting stress adaptation/pre-conditioning through osmoregulation. Osmoregulation results in the ability to maintain photosynthesis to a lower leaf water potential in preconditioned compared to well watered plant (Ackerson & Hebert 1981) and a reduction in leaf expansion (Thomas, Brown & Jordan 1976). There is also an increase in the leaf water potential necessary to trigger stomatal responses (Brown, Jordan & Thomas 1976, Sadras & Milroy 1996). Plant growth is generally maximised when the requirements for growth (e.g. radiation, CO2, water and nutrients) are in ready supply. A restriction in any of the requirements (e.g. radiation) is likely to reduce crop growth and therefore yield. However, the impact of an applied soil moisture deficit at specific growth periods can have a varied effect on crop yield. This is caused by differences in sensitivity to soil moisture deficit between various plants structures at each growth stage and re-deployment of photo-assimilates to less moisture sensitive structures (see Section 2.1.1).

Deficit irrigation (DI) in the context of this work is where by the volume of irrigation applied is less than the estimated crop water use, resulting in a net decline in plant available soil moisture content during the whole (or parts) of the season cycle of plant development. Regulated deficit irrigation is a form of deficit irrigation and the term is commonly used interchangeable with DI in literature. However, by definition RDI occurs when irrigation rates are applied which maintain plant water status within prescribed limits of deficit (with respect to maximum water potential) for a part (or parts) of the seasonal cycle of plant development, often when fruit growth is least sensitive to water reductions (Hutmacher *et al.* 1994, Kang, Shi & Zhang 2000, Kirda 1999, Marsal *et al.* 2002, Mitchell & Shennan 1991, Mpelasoka, Behboudian & Mills 2001, Torrecillas *et al.* 2000). DI strategies control vegetative and reproductive growth by regulating the photosynthetic assimilate supply to these plant structures. Successful DI aims to optimise the productivity of water use by reducing vegetative growth while minimising any reduction in yield that may occur from its implementation.

DI and RDI has been found to produce improved crop water use productivity for a variety of crops (Hutmacher *et al.* 1994, Kang, Shi & Zhang 2000, Kirda 1999, Marsal *et al.* 2002, Mitchell & Shennan 1991, Mpelasoka, Behboudian & Mills 2001, Torrecillas *et al.* 2000). Initial experiments with RDI in peaches and pears attempted to maximise fruit biomass by redeploying photo-assimilate from shoot growth and to achieve prescribed concentrations of sugar and other sensory qualities in wine produced from grapes (Kriedemann & Goodwin 2003). Maize has been found to benefit from RDI during the seedling and stem elongation stage by stimulating root development and enhancing the root-to-shoot ratio (Kang, Shi & Zhang 2000). Advanced fruit ripening and increased fruit total soluble solids in apples has also been found from the implementation of RDI (Mpelasoka, Behboudian & Mills 2001). DI has been demonstrated to also have proven water use productivity benefits (Kang, Shi & Zhang 2000, Mitchell & Shennan 1991). Similarly, Yazar, Sezen & Sesveren (2002) found no significant difference in cotton yields from DI when irrigating at either 50 or 100% of cumulative Class-A-pan evaporation.

2.2.2 Partial Rootzone Drying (PRD)

The role of the stress/growth hormone Abscisic Acid (AbA) has been well researched in recent times. Plants which experience stress due to drought, salinity and low temperature increase AbA concentrations in their plant tissues (Hartung, Wilkinson & Davies 1998). Elevated levels of AbA in response to soil moisture deficit has been found to originate from the plant's roots and act as a sensitive long distance chemical signal enabling the aerial plant components to adjust to the soil moisture status (Davies & Zhang 1991, Hartung, Sauter & Hose 2002, Jackson 1997, Zhang & Davies 1989, Zhang & Davies 1990, Zhang, Schurr & Davies 1987). Elevated levels of AbA in response to a soil moisture deficit aid the plant's drought mitigation response of conserving limiting water by causing a reduction in both stomatal aperture and vegetative growth (Comstock 2002, Davies, Wilkinson & Loveys 2002, Snaith & Mansfield 1982, Zhang & Davies 1990, Zhang, Outlaw & Aghoram 2001).

In a perennial or indeterminate crop, vegetative and stomatal reductions as a result of elevated levels of AbA could lead to reduced transpiration and vegetative growth, and improved water use productivity (Davies, Wilkinson & Loveys 2002). However, to achieve the elevated level of AbA required for a physiological response under a normal crop drying cycle, the soil moisture deficit would need to be greater than normally applied and a disruption to plant water status (i.e. loss of turgor) may occur.

Split root trials have been used to investigate drought response mechanisms and to evaluate AbA elevation and its effect of reduced stomatal aperture. Partial rootzone drying (PRD) is an irrigation strategy based on split-root technology which alternatively wets and dries (at least) two spatially separate parts of a plant's root system. This strategy aims to simultaneously maintain plant water status at maximum water potential while regulating stomatal behaviour and vegetative growth (Kriedemann & Goodwin 2003). PRD achieves this desired change in plant physiological response by elevation of AbA as a feed-forward mechanism. Hence, PRD enables the separation of the biochemical responses to water stress from the physical effects of reduced water availability (Loveys *et al.* 1997). The benefits of PRD are based around two theoretical premises (Kang & Zhang 2004):

(a) fully irrigated plants usually have widely opened stomata. A small narrowing of the stomatal opening may reduce water loss substantially with little effect on photosynthesis, and

(b) where part of the root system is in dry soil, the plant will respond by sending a root-sourced signal to the shoots where stomata may be inhibited so that water loss is reduced.

Hence, as photosynthetic rates show a saturation response as stomata open and transpiration rates show a more linear response, then a partial closing of stomata will substantially reduce water loss but have little effect on the rate of photosynthesis (Kang & Zhang 2004).

PRD originated from concurrent work being conducted on apples trees at the University of Lancaster, UK and on grapevines in South Australia. The first research involving PRD in apples investigated chemical plant signalling between plant's roots and shoots (Gowing, Davies *et al*. 1990). In these initial experiments, roots from individual plants were divided between two containers. One container was kept well watered and the other left to dry out. Roots located in the drying containers released elevated levels of AbA. In the presence of these elevated levels, it was noted that the plant inhibited leaf growth, reduced stomatal aperture and redirected sugars to fruit. Similar responses to elevated AbA from a partially drying root zone have been found in grapevines without producing any adverse effects on fruit yield (Loveys *et al.* 1998).

Various varieties of grapevines grown under PRD have been found to have reduced stomatal aperture and pruning weight, while still maintaining berry size and yield, leading to an increase in water use productivity (Gu *et al.* 2000, Loveys *et al.* 1997, Loveys *et al.* 1998). As well as these benefits, PRD in grapevines has also been found to cause significant increases in anthocyanin levels in fruit and titratable acidity, while other wine making characteristics such as brix readings and juice pH were maintained (Chalmers & Kirstic 2001, Loveys *et al.* 1998). Commercial use of PRD in vineyards is now being conducted, with improvements in water use productivity ranging from 86% for Shiraz at McLaren Vale to 90% for Riesling in the SA Riverland (Kriedemann & Goodwin 2003).

PRD irrigation has since been found to increase water use productivity in a variety of crops (e.g. sunflower, maize) by reducing evaporative losses during periods of limited soil moisture availability or high evaporative potential (Kang *et al.* 1998, Kang *et al.* 2000, Kang, Shi & Zhang 2000, Loveys *et al.* 1997, Loveys *et al.* 1998, Neales *et al.* 1989). Research is also currently being conducted into PRD for implementation on olives, citrus fruits, peaches, pears, tomatoes, aubergines and raspberries.

Elevation of AbA associated with drying only part of the root zone has been found to be of a transient nature (Loveys *et al.* 1997). However, alternating the irrigated side of grapevines on a 10-14 day cycle so that half of the root mass was always in a state of drying (Figure 2.5) has been found (Stoll, Loveys & Dry 2000) to maintain elevated AbA levels and the reduction in transpiration and growth.

It is important at this point to re-state the main difference between a PRD and a DI system. That is, the physiological responses resulting from a DI system are the result of a soil moisture deficit being imposed upon the plant causing a mild water stress. Physiological changes in plants grown under a PRD system are the result of chemical signalling from roots responding to a stress induced by a substantial soil moisture deficit in part of the root zone. However, as the 'wet' part of the root zone provides access to readily available water, the plant will still maintain its water status and not be placed under any significant stress.

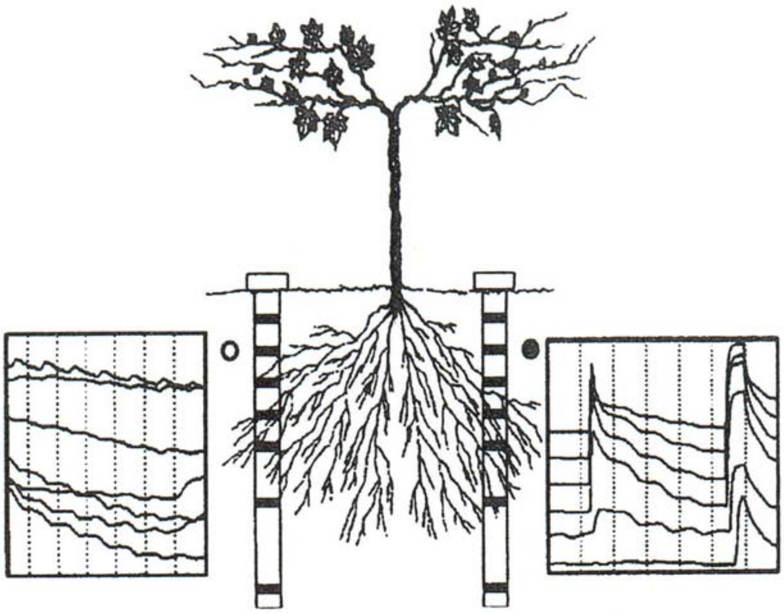


Figure 2.4 PRD in grapevines. Sub-surface drip lines supply water to one side or the other of the vine. In this diagram water is supplied through two irrigation cycles to the right hand line. The water content of the soil at various depths is shown as output from Environscan sensors. While the soil around the right hand sensor wets and dries in response to the irrigation, the soil on the left hand side of the vine continues to dry (Loveys *et al.* 1997)

2.3 Potential for Deficit Irrigation and Partial Rootzone Drying in the Australian Cotton Industry

2.3.1 Deficit Irrigation in Cotton

Various crops including wheat, sunflower, sugar beet, potato and cotton are well suited to deficit irrigation practices with reduced evapotranspiration imposed throughout the growing season (Kirda 2000). However, the adoption of a successful deficit irrigation strategy in any crop requires appropriate knowledge of the crop ET, crop response to water deficits (including the identification of critical crop growth periods) and the economic impacts of alternative deficit irrigation strategies (Pereira, Oweis & Zairi 2002).

Furrow irrigation is not well suited to maintain a mild deficit range (see Section 2.1.2) and the application of RDI. Centre pivots and lateral move machines are able to apply higher frequency irrigation applications of smaller volumes and are therefore well suited to the implementation of a DI or RDI system. Research has been conducted abroad into the benefits of deficit irrigation for cotton production using LMIMs and drip irrigation. Deficit irrigation trials conducted by Yazar, Sezzen & Sesveren (2002) using LEPA and drip systems, found no significant difference in seed cotton yields grown where 50%, 67% and 100 % of cumulative Class-A-pan evaporation was applied. Similar results were also reported by Hutmacher *et al* (1994) who found cotton yields were only slightly affected by reducing irrigation amounts to 0.6-0.7 of evapotranspiration. Bordovsky *et al* (1992) also found high frequency deficit irrigation with LEPA socks increased cotton lint yields and improved irrigation water use$_{\text{Applied}}$ index ($IWUI_{\text{Applied}}$ = yield / ML Applied). Little deficit irrigation research has been conducted locally within the Australian cotton industry. However, Bhattarai *et al*. (2003) found that implementing a deficit irrigation strategy using drip irrigation in central Queensland can improved $IWUI_{\text{Applied}}$. No research work has been conducted in Australia on RDI applied using LEPA socks fitted to LMIMs.

2.3.2 Partial Rootzone Drying in Cotton

Drought tolerant deciduous perennials such as cotton are expected to respond well to PRD (Davies, Wilkinson & Loveys 2002). However, the only PRD research in cotton has been conducted in Turkey (Topcu *et al*, 2002) using furrow and drip irrigation systems. In this research, PRD was implemented under furrow irrigation by irrigating every second furrow. The wetted furrows were then alternated either every, or every second, irrigation event. This strategy was found to improve water use productivity by 95% and 88%, respectively compared to an un-alternated furrow irrigated control treatment (Topcu *et al*, 2002). However, both the furrow and drip PRD treatments in this research received only half of the volume of irrigation water applied to the control treatment. Hence, it was impossible to separate the effects of deficit irrigation from those associated with PRD. Without either (a) direct measurement of AbA levels for each treatment, (b) plant water status measurements, and/or (c) the implementation of a second control treatment where the same quantity of water as the PRD treatment is applied to both sides, PRD effects cannot be isolated.

There is currently no published research work regarding the implementation of PRD strategies using LMIMs fitted with LEPA socks. However, LMIMs fitted with two metre spaced LEPA socks provide the opportunity to deliver water to the soil surface in every second cotton furrow. As LMIMs have the ability to apply variable irrigation application rates and frequency of irrigation, it is possible to impose and maintain soil moisture gradients across the root zone of the crop which may be conducive to creating a PRD signalling effect. The placement of each LEPA sock can also be easily alternated to the opposite side of the plant row to maintain root signalling. This may be done manually before each irrigation event or automated with a winching type design.

2.3.3 Climatic and Soil Based Limitations to the Implementation of DI and PRD

The implementation and maintenance of deficit or PRD irrigation strategy (in any crop) requires a high level of control over root zone soil moisture conditions. This requires precision in both the spatial and temporal control of irrigation applications. The use of either a centre pivot or lateral move machine enables a high level of control over irrigation volumes, timing and placement. However, environmental variables which are not able to be controlled and impact on the root zone soil moisture distribution include the soil physical and hydraulic properties and the presence of in-season rainfall.

Deficit irrigation is generally more successful in finely textured soils (Kirda 2000) as the larger available water content in these soils provides more time for the plant to adjust to the deficit conditions compared to sandy soils. However, the larger the soil water holding capacity the longer the period of crop water extraction required before the desired deficit condition is reached.

A possible limitation to the implementation of PRD on clay soils is the tendency towards a greater lateral movement of soil water. Hence, soil water may move from the nominally wet side of the rootzone to the nominally dry side reducing the soil moisture gradient and potentially inhibiting root signalling (Kriedemann & Goodwin 2003, Milroy & Tennakoon 2002). The ability to create the necessary soil moisture gradient may be further limited by the cracking nature of the Vertosol soils commonly found in the cotton industry and the small volume of water normally applied with LMIMs. Both of these factors may lead to macropore flow and the inability to maintain nominally 'wet' and 'dry' components of the root zone.

Kriedemann and Goodwin (2003) also suggest that in a clay loam soil, successive cycles of de-watering and re-wetting could be too long for effective PRD to occur (i.e. root signalling becomes dissipated, and shoot physiology remains unrestricted).

Deficit irrigation is difficult to achieve and maintain in areas where in-crop rainfall occurs regularly. The Australian cotton industry is predominately located in regions experiencing summer rainfall (i.e. in-season) and on heavy clay soils with large water holding capacities. Hence, the climatic and soil conditions common within the cotton industry may pose an impediment to the successful implementation of deficit irrigation strategies in Australia.

2.4 Research Opportunities and Specific Project Objectives

Deficit irrigation and partial rootzone drying have been shown (Section 2.2) to be effective strategies for improving water use productivity in a range of irrigated crops. While deficit irrigation has been shown to be effective at improving water use productivity in cotton, it is not widely used within the Australian cotton industry. Similarly, there has been little research conducted to identify whether cotton responds to partial rootzone drying and there is currently little understanding of the way in which DI and PRD strategies could be commercially implemented using LMIMs. Hence, this review has identified three main research questions which need to be addressed before guidelines for the commercial implementation of DI and PRD strategies using LMIMs can be developed for the Australian cotton industry:

(a) Does the application of partial rootzone drying produce a physiological response leading to improved crop water use productivity in cotton?

(b) Can the soil moisture conditions required to achieve deficit irrigation and partial rootzone drying be created under field conditions using large mobile irrigation machines?

(c) What are the regional soil and climatic constraints associated with the implementation of deficit irrigation and partial rootzone drying strategies within the Australian cotton industry?

To address each of these research questions the specific project objectives are to:

(a) characterise the biochemical and physiological responses of cotton associated with the implementation of PRD and RDI soil moisture conditions (Chapter 3),

(b) evaluate the physiological, yield and water use productivity responses of cotton to a range of PRD and DI treatments implemented under field conditions using commercial large mobile irrigation machines (Chapter 4), and

(c) quantify the effect of climatic and soil conditions on the potential to commercially apply PRD within the Australian cotton industry (Chapter 5).

3.0 PHYSIOLOGICAL RESPONSE OF COTTON TO SOIL MOISTURE DEFICITS AND PARTIAL ROOTZONE DRYING

There is currently insufficient evidence regarding the physiological responses associated with PRD and RDI in cotton to determine the environmental and management conditions for which these practices are likely to be beneficial under commercial conditions (Chapter 2). This chapter reports on a series of glasshouse experiments to characterise the biochemical and physiological responses of cotton associated with the implementation of moisture deficit and PRD conditions.

3.1 Introduction

Both hydraulic and non-hydraulic (biochemical) signals are involved in regulating plant growth and stomatal responses to changes (e.g. soil moisture availability, temperature, radiation and vapour pressure deficit) in the abiotic environment) (Comstock 2002, Davies & Jones 1991, Dodd, Stikic & Davies 1996, Munns *et al.* 2000, Sauter, Dietz & Hartung 2002). Recent research work (Comstock 2002, Davies, Wilkinson & Loveys 2002, Dodd 2003, Holbrook *et al.* 2002, Simonneau, Barrieu & Tardieu 1998, Snaith & Mansfield 1982, Zhang & Davies 1990, Zhang, Outlaw & Aghoram 2001) has identified that changes in xylem sap Abscisic Acid concentration ([AbA]) and sap pH corresponds to rootzone soil moisture availability and shows correlative evidence in reducing stomatal conductance and growth rate

Elevation of xylem sap [AbA] correlates well with reductions in stomatal conductance through its involvement in K+ uptake, which is the driving force for maintaining turgor and stomatal aperture (Roberts & Snowman 2000). Alkalinisation of sap pH has also been found to reduce stomata conductance without the need for a change in concentration of Abscisic Acid (AbA) (Bahrun *et al.* 2002, Dodd 2003). However, the presence of AbA is required and stomatal conductance is therefore an AbA-dependent mechanism (Bacon, Wilkinson & Davies 1998, Wilkinson *et al.* 1998, Wilkinson & Davies 1997). The sensitivity of stomatal response to AbA is also increased under nitrogen deprivation most likely due to increased alkalisation of the sap pH (Bahrun *et al.* 2002, Dodd, Tan & He 2003, Radin, Parker & Guinn 1982). Leaf elongation rate (broadly, vegetative growth) is also reduced as sap pH is alkalinised and/or xylem sap [AbA] elevated (Bacon, Wilkinson & Davies 1998, Wilkinson & Davies 1997).

PRD is a biochemically driven irrigation strategy that aims to improve crop water use productivity (see Section 2.2.2). Improved water use productivity is achieved by simultaneously maintaining plant water potential (through readily available soil moisture on the 'wet' side), while increasing biochemical signalling from roots located on the 'dry' side. This results in a partial reduction in stomatal conductance (g_s) and a decrease in vegetative growth rate. The increase in CO_2 absorbed (i.e. carbon assimilation) to H_20 expelled (i.e. transpiration) and the reduction in excessive vegetative growth both result in improved crop water use productivity.

Regulated deficit irrigation (RDI) is also an irrigation strategy which aims to improve crop water use productivity (see Chapter 2.2.1). However, RDI achieves this by reducing soil moisture availability during phrases of crop growth which demonstrate either no, or limited, response in terms of yield. The major distinguishing factors between PRD and RDI are the differences in their implementation, the effect on localised soil moisture conditions and plant water status. PRD aims to maintain a favourable plant water status and create a physiological response due to biochemical signalling only. RDI does not maintain plant water status and does not achieve the same level of biochemical signalling as PRD (Kriedemann & Goodwin 2003).

A variety of crops have been found to have an improved crop water use productivity under PRD (Kang *et al.* 1998, Kang *et al.* 2000, Kriedemann & Goodwin 2003, Loveys *et al.* 1997, Loveys *et al.* 1998, Neales *et al.* 1989) and RDI (Hutmacher *et al.* 1994, Kang, Shi & Zhang 2000, Kirda 1999, Marsal *et al.* 2002, Mitchell & Shennan 1991, Mpelasoka, Behboudian & Mills 2001, Torrecillas *et al.* 2000). However, little research has been conducted into the biochemical responses and the water use productivity benefits of PRD and RDI in cotton. Hence, the aim of this research was to characterise the biochemical response of cotton to regulated deficit irrigation and partial rootzone drying and to investigate whether these strategies have any impact on stomatal response and/or vegetative growth which leads to an improvement in crop water use productivity.

3.2 Methodology

A series of four glasshouse trials were conducted to investigate the physiological response of cotton to soil moisture deficit and partial rootzone drying. The trials investigated the effect of:

(a) non-alternated PRD and RDI management strategies on plant growth (Trial 1 = T1) and AbA production (Trial 3 = T3), and

(b) PRD alternation strategy and RDI on AbA production and physiological responses (Trials 2 & 4 = T2 & T4).

Each glasshouse trial was conducted in the Faculty of Science glasshouse complex, University of Southern Queensland, Toowoomba. Trials were conducted during the 2002/2003, 2003/2004 and 2004/2005 summer seasons. The glasshouse temperature was maintained at 25^{O}C throughout the trial. Mean daily day degrees (DD) was equal to 12. DD = ((minimum temperature – 12) + (Maximum temperature – 12)) / 2.

3.2.1 Plant Management

The cotton variety Sicot 80 (Cotton Seed Distributors, Wee Waa, NSW) was used in all trials. Four to five seeds were planted into well-watered Peat 80 Plus potting mix (Searles, Pty Ltd, Kilcoy) in 140 mm round black pots at a depth of 50 mm. During establishment, pots were sprinkler irrigated daily to drainage. The seedlings were thinned to one plant per pot 10-15 days after planting (DAP). Seedlings were transplanted after reaching the four true leaf stage. Seedlings were transplanted by immersing each pot in water, removing the pot and washing out all potting mix from between the roots. This was conducted as gently as possible to ensure minimal damage to the roots.

For T1, seedlings were transplanted into 380 mm diameter round pots containing a plastic divider placed down the middle of each pot (Plate 3.1). Each plastic divider had a 20 mm wide and 80 mm deep U-shaped cut taken out of the middle. The pots were filled with soil up to the bottom of the U-shaped cut in the plastic divider and watered. A plant was then placed on top of the U-shaped cut with roughly equal root masses placed on each side of the plastic divider. The taproot was typically poorly developed at transplanting and was placed on a pre-marked side of the divider which was the “dry” side in the subsequent treatments. The roots were then covered with moist soil up to the same level on the plants as prior to transplanting. The soil used in T1 was collected from the 0-20 cm surface layer of a Black Vertosol (Isbell 1996) located on ‘Macquarie Downs’ (coordinates S270 54.176', E1510 30.871), between Leyburn and Millmerran on the eastern Darling Downs, Queensland.

Plate 3.1 Cotton seedling transplanted over the plastic pot divider, T1

The transplanting procedure in T2 was the same as for T1 except that two seedlings were transplanted into each of the pots with their roots evenly divided across the plastic divide (Plate 3.2). The tap roots from the two plants were located on opposite sides of the plastic divider.

Plate 3.2 Plastic divider used in PRD pots with two U-shaped cuts, T2

For T3 and T4, plants were transplanted into two 175 mm wide, 4.5 litre square pots which were pop riveted together and had the same U-shaped gap cut-out from between the two pots (Plate 3.3). A low soil moisture potential (~ 2 kPa) was maintained in the well watered (i.e. "wet") pots by equilibration with a free water table at the base of the pot. Geofabric ® was placed in the base of each pot to inhibit root growth into the saucer and soil loss. The transplanted cotton plants were placed with approximately equal root mass in each of the two joined pots with the taproots bias to a predetermined side. Geofabric® was also placed over the top of the soil surface to reduce soil moisture evaporation.

Plate 3.3 Twin-pots used in T3 and T4

The soil used in T3 and T4 was a Coal Fines Paunch Mix (Superior Sand and Gravel Landscaping, Toowoomba). This soil blend had a low soil moisture holding capacity and was used to reduce soil dry down time. It was also chosen due to its higher air filled porosity which ensured there was no waterlogging associated with the free water surface at the base of the pots. The air filled porosity of the soil at equilibrium was greater than 0.10 $cm^3\ cm^{-3}$ which is the threshold for waterlogging responses in cotton (Hodgson & Chan 1982).

Each soil utilised in the trials was passed through a 20 mm sieve before use and Ozmocote (Scotts Australia Pty Ltd, Baulkham Hills) slow release fertilizer was incorporated at a rate of nitrogen equivalent to a field application of 200 kg of Urea ha^{-1}.

3.2.2 Trial Design

3.2.2.1 Effect of Non-alternated PRD on Plant Growth

The T1 trial consisted of 20 pots laid out in a completely randomised block design of four treatments by five blocks, located along one glasshouse bench running North-South. Within each block, the four treatments were randomly allocated to the four pots. Treatments consisted of:

(a) Control - soil moisture allowed to dry down to an average of 100 kPa on both sides of the plastic divider and then re-irrigated on both sides back to field capacity,

(b) 50 kPa - soil moisture allowed to dry down to a target of 50 kPa on the ‘wet’ side and then re-irrigated on ‘wet’ side back to field capacity,

(c) 100 kPa - soil moisture allowed to dry down to a target of 100 kPa on the ‘wet’ side and then re-irrigated on ‘wet’ side back to field capacity, and

(d) 200 kPa - soil moisture allowed to dry down to a target of 200 kPa on the ‘wet’ side and then re-irrigated on ‘wet’ side back to field capacity.

Soil moisture was measured using gypsum blocks (TAIN Electronics, Melbourne) buried in the middle of each pot. Field capacity was assumed when the gypsum blocks read below 20 kPa and/or when pots were noted to be free draining.

3.2.2.2 Effect of Non-alternated PRD on AbA Production

The T3 trial consisted of 95 pots laid out over three blocks by two treatments. The trial was initiated 45 DAP to allow the plants to recover from being transplanted. The treatments were:

(a) Control - a free water surface was maintained at the base of both pots which were joined and

(b) Non alt. PRD - a free water surface maintained at the base of only one pot while the other side (i.e. with the tap root) was allowed to dry down over the period of the trial.

3.2.2.3 Effect of Alternated PRD on Plant Growth

A range of PRD strategies and stress levels were evaluated in the alternated PRD trials (T2 & T4). In T2, alternation was based on a set period of time and in T4 alternation was based on threshold soil moisture values previously found to be associated with AbA signalling in the dry area of the root zone. In both trials there was a well-watered Control (irrigated on both root sides) and a non-alternated PRD treatment irrigated on only one side to separate differences between PRD and RDI.

T2 consisted of 25 pots arranged in a completely randomised blocked design with five treatments and five blocks. The treatments implemented were:

(a) Control (2W) - soil moisture maintained between 30 and 60 kPa on both sides of the pot,

(b) RDI Control (W) - soil moisture maintained between 30 and 60 kPa on one side of the pot only allowing the other side to dry down,

(c) 5 day alt. (5Alt) - soil moisture maintained between 30 and 60 kPa on one side of the pot only and then alternated to the opposite side back to within 30-60 kPa after approximately 5 days,

(d) 10 day alt. (10Alt) - soil moisture maintained between 30 and 60 kPa on one side of the pot only and then alternated to the opposite side back to within 30-60 kPa after approximately 10 days, and

(e) 15 day alt. (15Alt) - soil moisture maintained between 30 and 60 kPa on one side of the pot only and then alternated to the opposite side back to within 30-60 kPa after approximately 15 days.

T4 consisted of 50 pots arranged in a completely randomised blocked design of five treatments by 10 blocks spread across four rows on two benches. Treatments implemented were:

(a) Control 2 Wet- soil moisture maintained with a shallow water table beneath both pots,

(b) PRD No Alt - soil moisture maintained with a shallow water table beneath one pot and the other pot allowed to dry down,

(c) PRD16% - soil moisture maintained with a shallow water table beneath one pot and alternated to the other pot once the pot drying down reached an average 16% volumetric soil moisture,

(d) PRD10% - soil moisture maintained with a shallow water table beneath one pot and alternated to the other pot once the pot drying down reached an average 10% volumetric soil moisture, and

(e) PRD10% + 4 days - soil moisture maintained with a shallow water table beneath one pot and alternated to the other pot 4 days after the pot drying down reached an average 10% volumetric soil moisture.

3.2.3 Plant Measurements and Soil Moisture Monitoring

3.2.3.1 Effect of Non-alternated PRD on Plant Growth

Plants in T1 were individually measured and mapped three times weekly. Measurements included plant height, number of fruiting (sympodia) branches and fruiting sites. To account for any pre-treatment difference in plants which may have arisen due to transplanting, pre-treatment plant height measurements were deducted from measurements taken at each date before analysis. Soil moisture was monitored on each side of the pot using gypsum blocks (TAIN Electronics, Melbourne) which were installed before transplanting of the seedlings. Gypsum blocks were located in the middle of each side of the pots at 200 mm depth. For two treatment blocks of pots, the gypsum block sensors were connected to loggers recording at 15 minute intervals while the sensors in the other treatment blocks were manually read three times each week (Plate 3.4).

(a)

(b)

Plate 3.4 T1 pots with gypsum blocks connected to (a) a logger box and (b) a manual reader

The trial was terminated when the Control plants had an average of 14 fruiting nodes and 5.3 nodes above white flower. All plants were individually harvested and plant dry weights were recorded. The pot soil was washed through a 4.25 μm sieve and the dry root mass for each pot and pot side recorded. The tap root was cut at a root diameter of 2 mm and the remaining root mass weighted to enable direct comparisons between the two root masses on each side of the plant to be undertaken without bias due to the subsurface stem base/root trunk.

3.2.3.2 Effect of Non-alternated PRD on AbA Production

Destructive plant and soil sampling was conducted every three to four days throughout the T3 trial and included measures of stem water potential (Ψ_s), xylem sap, plant dry weight and soil water content. Four plants from both the Control and PRD treatments were sampled, except on the last sampling day when the remaining eight plants from each treatment were sampled. Stomatal conductance measurements were obtained during the trial using a Li-COR 6400 portable photosynthesis system (LI-COR Inc, Lincoln, Nebraska). Quantum flux was set to match cloudless midday conditions in the glasshouse, CO_2 reference gas was set at 380 μmols mol^{-1} and block temperature was set at 30 ^{0}C. 'Matching' of the infra-red gas analysers was conducted after every 10th sample measured. Measurements were conducted on the youngest fully expanded leaf of each plant. One sample per leaf was measured at 10, 12 and 17 days after trial initiation (DATI). Two samples per plant were taken at 19 DATI and three samples per leaf were measured at 21 DATI.

Stem water potential (Ψ_s) was measured with a Scholander pressure chamber. Ψ_s measurements were conducted on the lowest main stem leaf at solar noon on the day before each plant was to be destructively sampled. The leaf was covered and sealed with aluminium foil for approximately 2 hrs before measurement. Ψ_s was measured instead of leaf water potential (Ψ_l) to account for whole plant evaporative demand (plant water status) and overcome variance in Ψ_l which can arise due to differences in individual leaf conditions, position, exposure and rates of water loss. Ψ_s is considered a better indicator of plant water status than Ψ_l (Remorini & Massai 2003).

Xylem sap was collected by destructive sampling using a technique similar to that of Bahrun *et al* (2002). Xylem sap was collected at dawn to ensure sufficient root pressure was present to collect approximately 0.5 cm^3 of sap. Root over pressure was not applied to obtain the sap sample as this may introduce inaccuracies (Bacon, Wilkinson & Davies 1998, Wilkinson *et al.* 1998). Plants were de-topped 20 - 30 mm from the soil surface and the cut surface cleaned with deionized water to remove any contaminants originating from cut cells. Disposable plastic eye droppers with a graduated tip were used to collect the sap samples. The eye dropper was placed over the plant stump and sealed with parafilm before being covered with aluminium foil to minimise contamination, photo degradation and radiant heat (Plate 3.5). Sufficient sap was collected within 1 hr of being de-topped. Sap samples were transferred into pre-cooled micro tubes (1 cm^3) and placed in an ice packed dark box for transport before being stored in a –75 ^{0}C cold room until analysis.

Plate 3.5 Extraction of xylem sap using an eye dropper and natural root pressure

The concentration of Abscisic Acid ([AbA]) in the stem sap was measured using an enzyme linked immunosorbent assay (ELISA) test (Phytodetek®ABA Enzyme Immunoassay Test Kit, Agdia, Elkhart, Indiana, USA). A preliminary dilution of sap samples was conducted to ensure the [AbA] was within the sampling range required for maximum accuracy. Sap pH was measured with an Orion combination needle pH electrode (Orme Scientific LT., Manchester, UK) fitted to a pH meter (Hanna Instruments, Melbourne). The pH electrode was cleaned between each sap sample by being placed in a cleaning solution (0.1N HCL) for 2 minutes before being rinsed with reverse osmosis deionised water. The electrode was also re-calibrated after every 10 sap samples.

Soil samples were taken at a depth of 125 mm in each pot after each plant was de-topped. Soil samples of known volume were weighed, placed in an oven at 105 °C for 48 hours and then left to cool in a desiccator vacuum for four hours before being re-weighed to calculate the volumetric soil moisture content. Soil water potential at sampling was calculated using the soil moisture characteristic for the potting medium, which was measured using repacked soil cores and the pressure plate method (McKenzie, Coughlan & Cresswell 2002).

3.2.3.3 Effect of Alternated PRD on Plant Growth

Agronomic measurements were collected every three days during T2 and T4 and included plant height, internode length, fruiting (sympodia) branches, fruiting sites and retention rates. Final plant dry weight and leaf area were also measured with a planimeter for both trials. Leaf area was estimated throughout the T4 trial using whole plant individual leaf length measures and a regression (Figure 3.1; R^2 = 93.45%) developed in a preliminary trial similar to that conducted by Constable and Gleeson (1977). In each case, leaf length was measured from the division of the main leaf vein to the tip of the leaf.

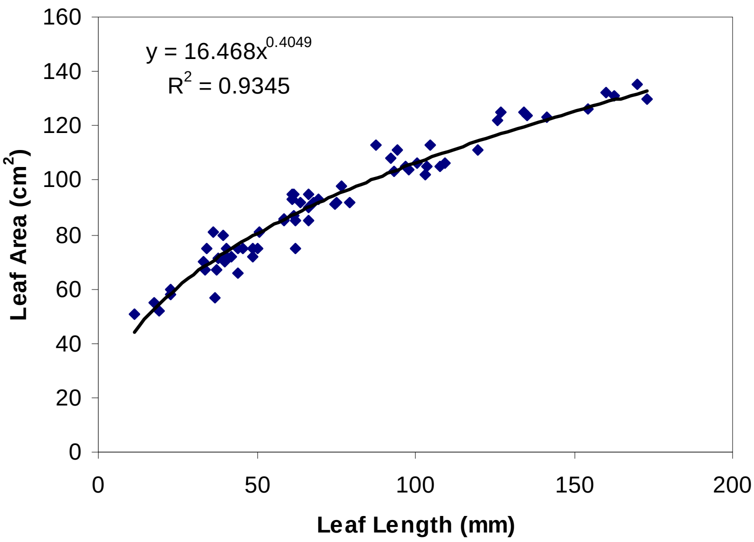


Figure 3.1 Relationship between leaf length and leaf area

Plant height was measured from the top of each pot to the growing tip of each plant. Internode length was measured between the fourth and fifth internode, with the youngest node denoted as the youngest main stem fully expanded leaf greater than 20 mm in diameter. Fruiting structures greater than 2 mm in diameter were counted and retention was calculated as the percentage of these fruiting structures which were retained. Harvested plant samples were dried at 40°C for 48 hours, except for the bolls which were cut in half and allowed to dry in an oven at 40°C until a stable mass was reached.

Soil moisture potential was monitored during T2 using both a gypsum block (TAIN Electronics, Melbourne) and a SoilSPEC® (H&TS Electronics, Melbourne) tensiometer both installed at a depth of 200 mm on each side of the plastic divider (Plate 3.6a). The tensiometer was used to measure soil water potentials of <80 kPa and the gypsum blocks used to record soil water potentials >80 kPa. The soil moisture content was measured daily throughout T4 using a calibrated Micro-Gopher® (Dataflow Systems, Christchurch, N.Z) using access tubes installed in the middle of each of the square pots (Plate 3.6b). The Micro-Gopher® was calibrated by fitting a linear regression between measured volumetric soil moisture obtained from destructive soil samples (collected in triplicate from around the gopher tubes with density rings) and Micro-Gopher® readings (Appendix A).

(a) **(b)**

Plate 3.6 (a) Gypsum blocks and tensiometers installed each side of plastic divide in T2 pots and (b) Micro-Gopher access tube installed in T4 pots

3.2.4 Statistical Methods

All data sets were tested for compliance with the underlying ANOVA assumptions. Data sets found to violate the ANOVA assumption of normality were transformed to improve the symmetry of the distribution prior to analyses. Levene's test for homogeneity was used to test the equal variance assumption. Where the Levene's test found heterogeneity, but the ratio of the largest to smallest sample standard deviation was less than two, the data set was considered suitable for ANOVA as the p-values for ANOVA are only mildly distorted with partially heterogenous data sets (Ott 1988). However, where the ratio of the largest to smallest sample standard deviation exceeded two, the $P = 0.01$ significance level was used to limit the occurrence of Type 1 errors. Unless otherwise stated, the level of significance was tested at $P = 0.05$.

Data were analysed using GenStat (Sixth Edition) and SPSS for Windows (version 11.5.0 and 12.0.1). A one-way ANOVA was conducted on the T1 data using GenStat and a Univariate ANOVA was conducted on the T3 data using SPSS for Windows (version 12.0.1). A general linear model (GLM) repeated measures ANOVA was conducted on the T2 data using SPSS for Windows (version 11.5.0). A GLM was also used to assess significance differences between cotton plants in T4 based on dry weights and leaf area using SPSS for Windows (version 12.0.1). Two-way repeated measures were used to detect significant differences in plant height, fruiting sites and retention. The GLM repeated measures were used to investigate significant change over time to reduce the occurrence/frequency of type one error which can occur when analysing each sampling day's data separately. Tukey (Post-hoc, multiple pairwise comparison) tests were used to identify significant differences between individual treatment groups.

3.3 Results

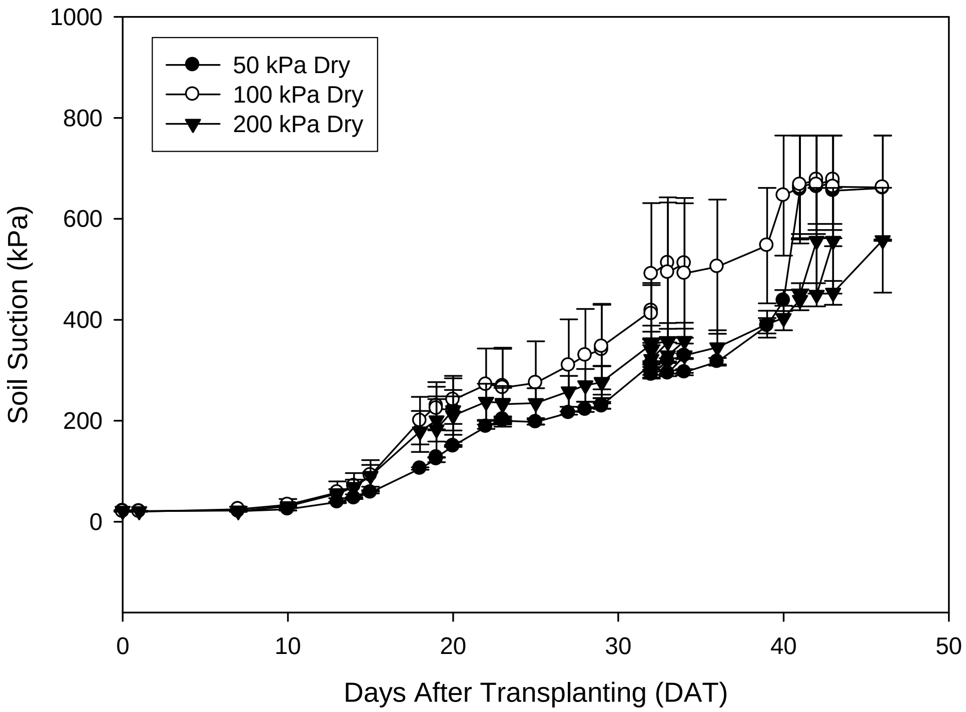
3.3.1 Effect of Non-alternated PRD on Plant Growth

All treatments received three irrigations during the trial except the Control which only received two irrigations. In general, the soil on the irrigated (i.e "wet") side of the plant was found to be drier prior to irrigation than the planned target deficit levels (Table 3.1). However, there were significant differences in soil moisture between the wet and dry side of the pots (Figure 3.2). Soil moisture on the 'dry' side of the pots increased throughout the trial to above 500 kPa in all the treatments and above 600 kPa in the 50 and 100 kPa treatments (Figure 3.2).

Table 3.1 Irrigations applied and soil moisture potential readings prior to irrigation

		Average Soil Water Potential (kPa) prior to irrigation	
1ST IRRIGATION	**Treatment**	**'Wet' side**	**'Dry' side**
22 DAT	50	72	188
18 DAT	Control (100)	198	249
18 DAT	100	200	200
18 DAT	200	249	178
2ND IRRIGATION			
32 DAT	50	101	312
36 DAT	Control (100)	146	168
32 DAT	100	143	418
32 DAT	200	193	351
3RD IRRIGATION			
41 DAT	50	154	658
-	Control (100)	-	-
41 DAT	100	156	662
40 DAT	200	358	556

(a)



(b)

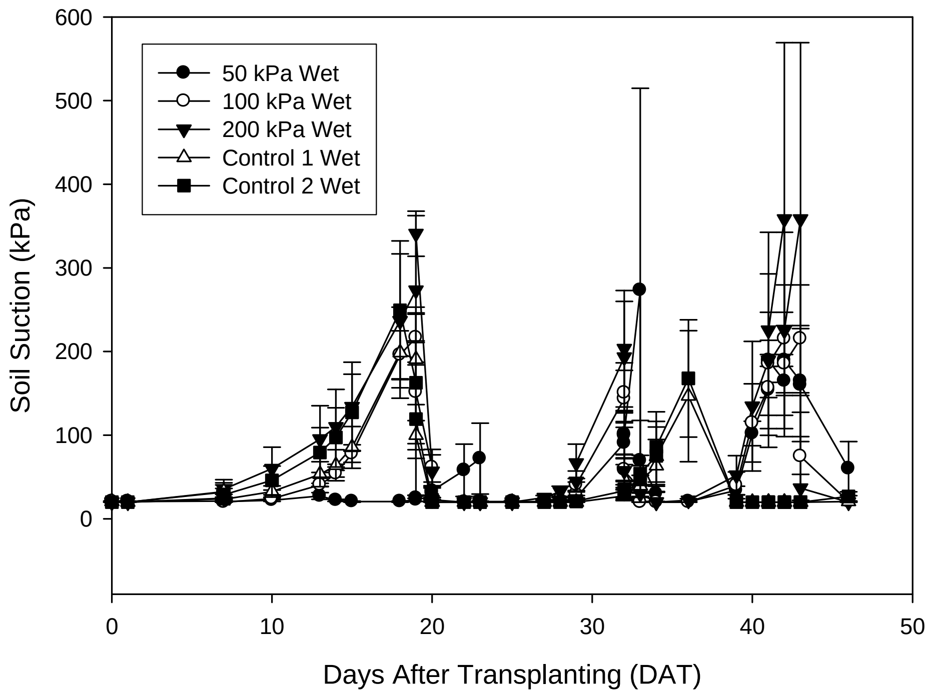


Figure 3.2 Average soil moisture measured on (a) dry and (b) irrigated side for each treatment (blocks 2-4)

NB: Error bars signify S.E. (n = 3)

Increasing the soil moisture deficit at which one side of the plant was irrigated was found to significantly reduce the plant height during the period of the trial (Figure 3.3). Irrigation at a target deficit of 100 kPa on both sides of the plant (i.e Control treatment) resulted in significantly taller plants 46 days after transplanting (DAT) (i.e. 90 days after planting) compared to when irrigation was applied at a target deficit of either 100 or 200 kPa to only one side of the plant (Figure 3.3). However, there was no significant difference in plant height where both sides of the plant were irrigated at 100 kPa (i.e. Control treatment) and where only one side of the plant was irrigated at 50 kPa. There was also no significant difference in plant height between the 100 and 200 kPa treatments. Similar results were found for plant mass (Table 3.2) with a highly significant (P=0.01) increases in above ground mass for the treatments which were applied at lower deficits (ie. Control and 50 kPa) compared to those where larger deficits were applied (ie. 100 and 200 kPa). There was no significant difference in washed root mass between any of the treatments (Table 3.2).

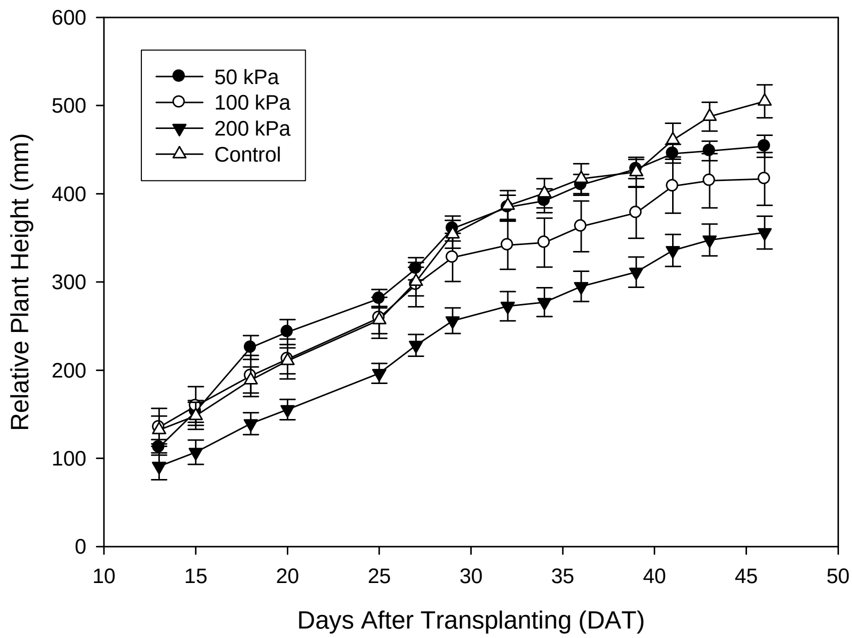


Figure 3.3 Effect of non-alternated PRD target deficit on height of cotton plants

NB: Plant heights are less pre-treatment height, error bars represent S.E (n = 5)

Table 3.2 Effect of non-alternated PRD target deficit on plant and root mass (46 DAT)

Treatment	Above ground plant mass (g)	Root mass (g)
Control	30.8 a	6.0 c
50 kPa	30.1 a	7.5 c
100 kPa	21.9 b	5.8 c
200 kPa	18.9 b	6.0 c

Figures followed by the same letter are not significantly different from each other (P = 0.01)

Increasing the target deficits for PRD irrigations tended to reduce the number of fruiting branches (Figure 3.4) and fruiting sites (Figure 3.5) throughout the trial. For the final measurement date, the only significant difference (at P = 0.10) in fruiting branches was between the Control (9.2 +/-0.7) and 200 kPa (7.4 +/-0.2) treatment. Similarly, the only significant (P=0.05) difference in fruiting sites at the final measurement date was between the Control (18.8 +/-1.8) and 200 kPa (13.0 +/- 0.6) treatments. There were no significant differences observed for the final percent retention of bolls (data not shown).

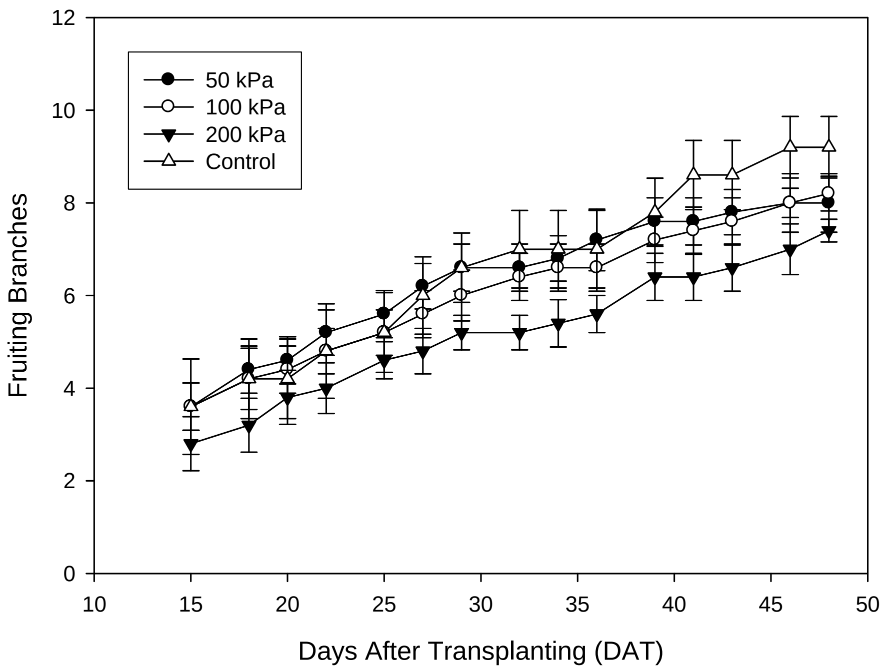


Figure 3.4 Effect of non-alternated PRD soil moisture conditions on number of fruiting branches

NB: Error bars represent S.E (n = 5)

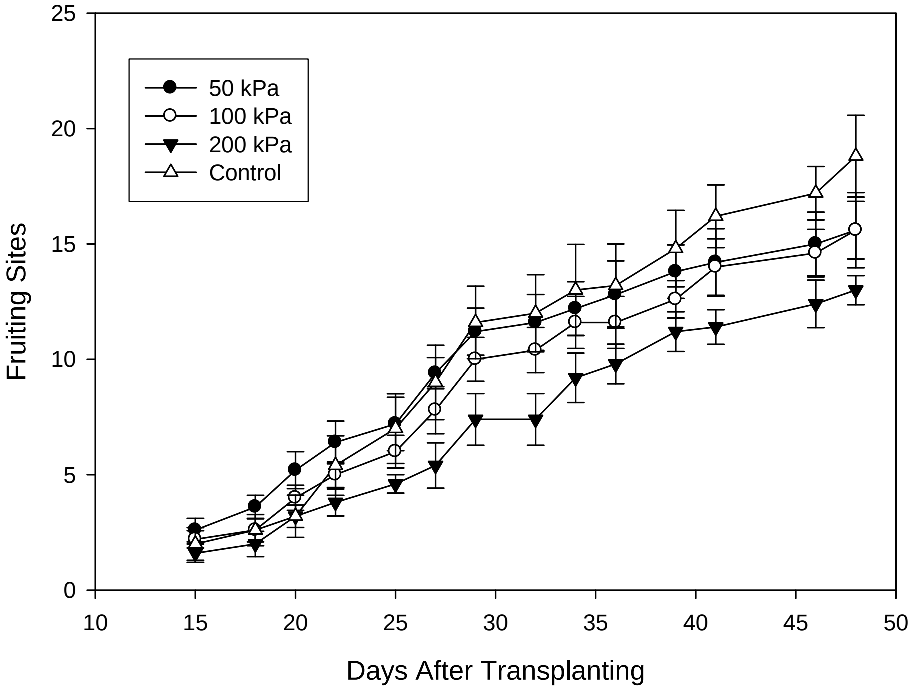


Figure 3.5 Effect of non-alternated PRD soil moisture conditions on fruiting sites

NB: Error bars represent S.E (n = 5)

3.3.2 Effect of Non-alternated PRD on AbA Production

Soil moisture on the 'dry' side of the non-alternated PRD treatment was found to decrease from an initial 29.3 (+/- 1.1) to 9.3 (+/- 0.4) % over the 24 days of the T3 trial (Figure 3.6). Saturated water content was 31.6 % and residual water content (i.e. at 1500 kPa) was 13.0 % for the soil media used. The soil moisture extraction on the 'dry' side of the Non-alt. PRD treatment was minimal by day 15 with a volumetric soil moisture content of 11.6 (+/- 0.4) % (i.e. approximately 2360 kPa).

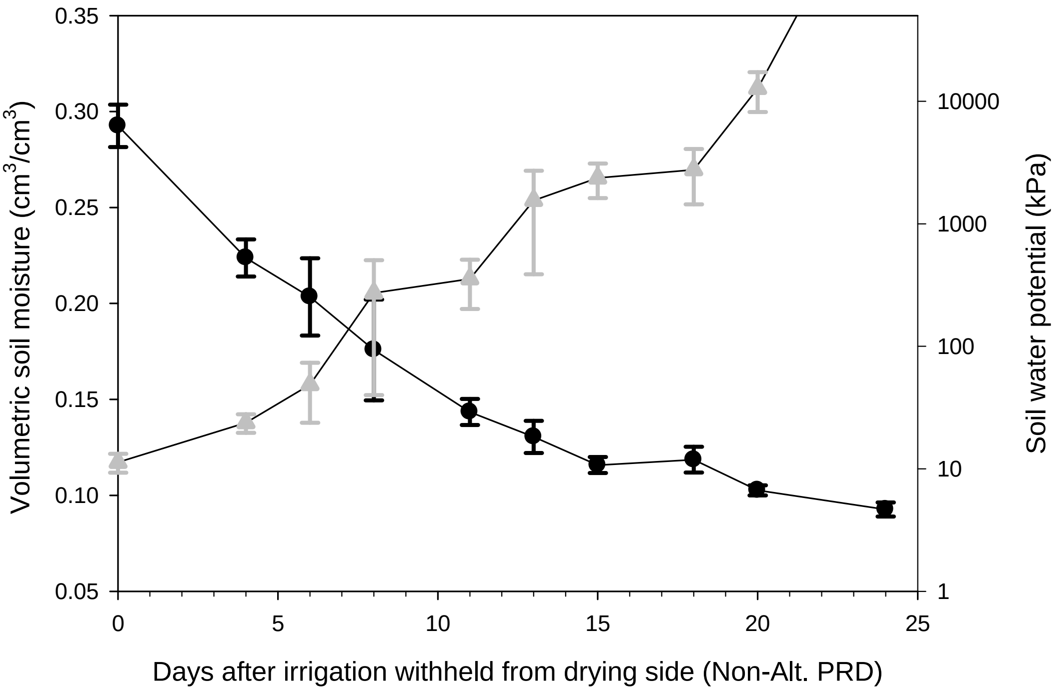


Figure 3.6 Volumetric soil water (●) and soil water potential (▲) on drying side of non-alternated PRD treatment. Data are means (n = 4) with standard errors

NB: Errors bars represent 95% Confidence Interval

There was no significant difference in stem water potential between the Control and Non-alt. PRD treatment at any sampling date (n = 4) except for 21 days after irrigation withheld (DAIW) when the PRD treatment was significantly higher than the Control (n = 8) (Figure 3.7). The small but significant difference between the non-alternated PRD and well watered Control treatments measured at 21 DAT was due to the increased sampling size. Variation in daily photosynthetically active radiation, temperature and vapour pressure deficit (VPD) can influence plant water potential, stomatal conductance, AbA production and AbA removal within plants (Gutschick 2002, Trejo, Clephan & Davies 1995, Trejo, Davies & Ruiz 1993, Wilkinson & Davies 2002). Hence, as the comparison and interpretation of [AbA] and stomatal conductance measurements taken on different days is difficult, this data

(Figures 3.8 and 3.9) is presented relative to the Control at each sampling date. Two distinct peaks in xylem [AbA] were observed during the trial (Figure 3.8).

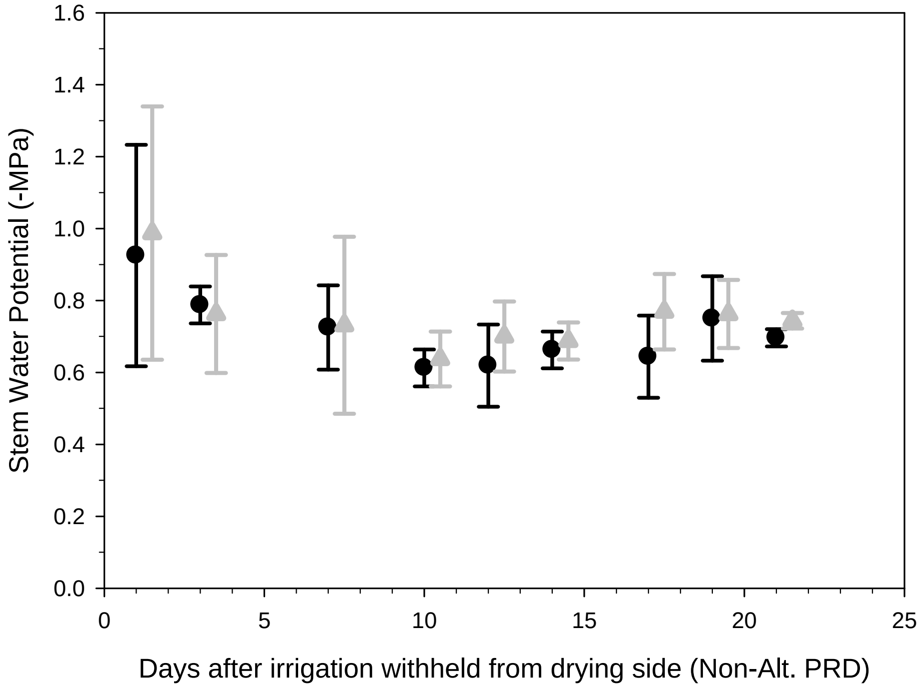


Figure 3.7 Effect of non-alternated PRD applied to cotton on stem water potential

Control (●) and Non-alternated PRD treatment (▲) sampled on same day, non-alternated PRD treatment offset ½ day ahead on graph for clarity. Data are means with 95% confidence intervals (n = 4 except for 21DAT where n = 8)

The first elevation in [AbA] was greater than a two fold increase over the [AbA] in the Control and occurred at 6 to 8 DAIW corresponding to an average soil moisture of 17.6 (+/- 2.6) to 20.3 (+/- 2.0) % (i.e. 271 to 354 kPa) on the 'dry' side (Figure 3.8). The second peak in [AbA] represented a four fold increase over the Control and occurred at 15 DAIW with an average soil moisture of 11.6 (+/- 0.4) % (i.e. approximately 2360 kPa). There was no significant difference measured in either stomatal conductance (Figure 3.9) or stem sap pH (Figure 3.10) on any of the sampled days for the Control and Non-alt. PRD treatments. There was a large variance observed in sap pH and no significant difference or trend in sap pH was found over the sampling period.

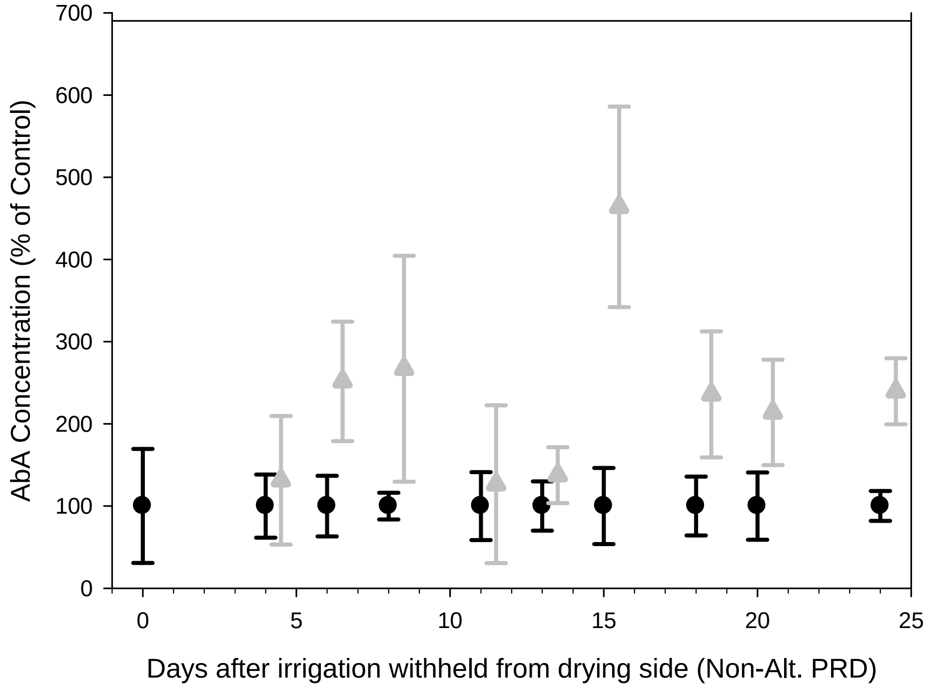


Figure 3.8 Effect of non-alternated PRD applied to cotton on Abscisic Acid concentration of xylem

Control (●) and Non-alternated PRD treatment (▲) sampled on same day, Non-alternated PRD treatment offset ½ day ahead for graph clarity. Data are means with 95% confidence intervals (n = 4)

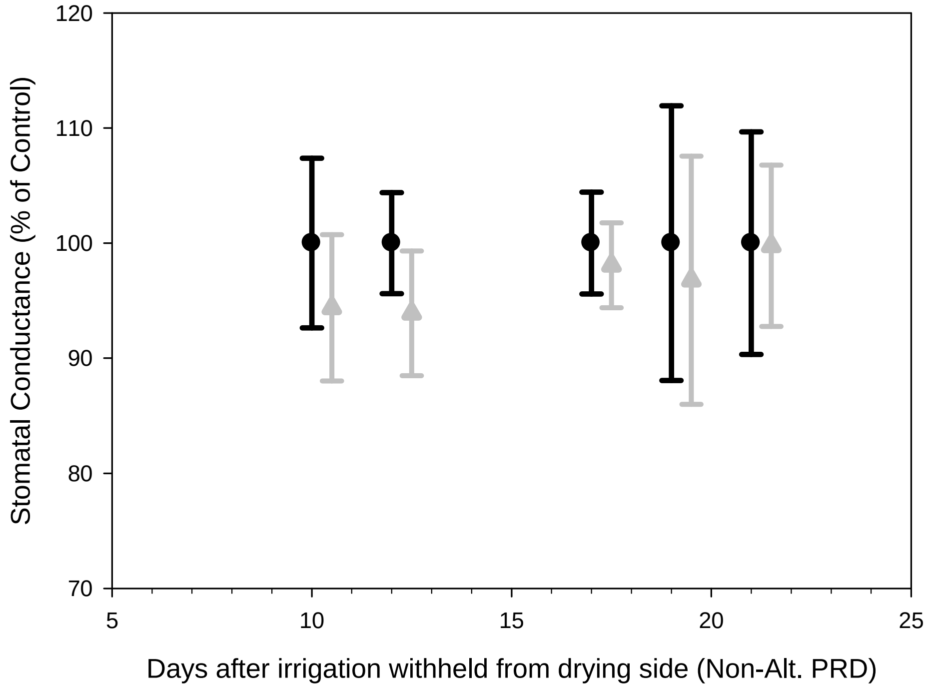


Figure 3.9 Effect of non-alternated PRD applied to cotton on stomatal conductance

Control (●) and Non-alternated PRD treatment (▲) sampled on same day, Non-alternated PRD treatment offset ½ day ahead for graph clarity. Data are means with 95% confidence intervals (n = 8+)

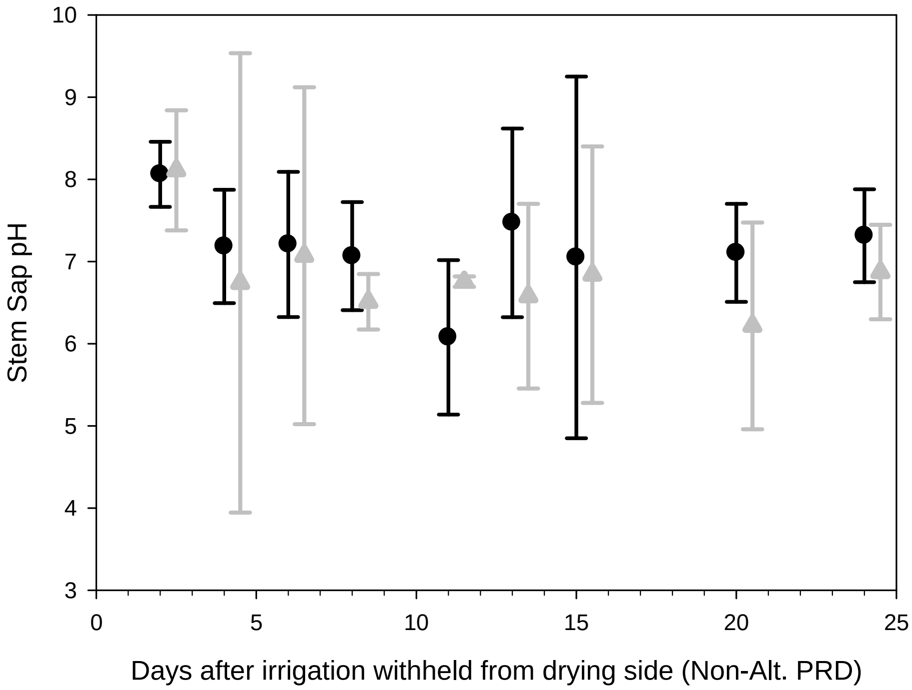


Figure 3.10 Effect of non-alternated PRD applied to cotton on stem sap pH

Control (●) and Non-alternated PRD treatment (▲) sampled on same day, Non-alternated PRD treatment offset ½ day ahead for graph clarity. Data are means with 95% confidence intervals (n = 8)

3.3.3 Effect of Alternated PRD on Plant Growth

Trial 2 (T2)

A general trend in plant height was observed during T2, with the Control treatment (2W) being significantly taller than all other treatments from 64 DAT (89 DAP) onwards (Figure 3.11). The 5Alt and 10Alt plants were shorter than the Control plants, but significantly taller than the 15Alt and the non-alternated W plants from 80 DAT (105 DAP) onwards which were never significantly different from each other (Figure 3.11). A highly significant (P = 0.01) difference in final plant leaf area and a significant (P = 0.05) difference in final plant dry weight was found between the Control (2W) and all other treatments which were not significantly different from each other (Table 3.3). No significant difference (P = 0.05) was present between any treatments in terms of crop water use productivity when calculated using final dry weight achieved divided by total water applied.

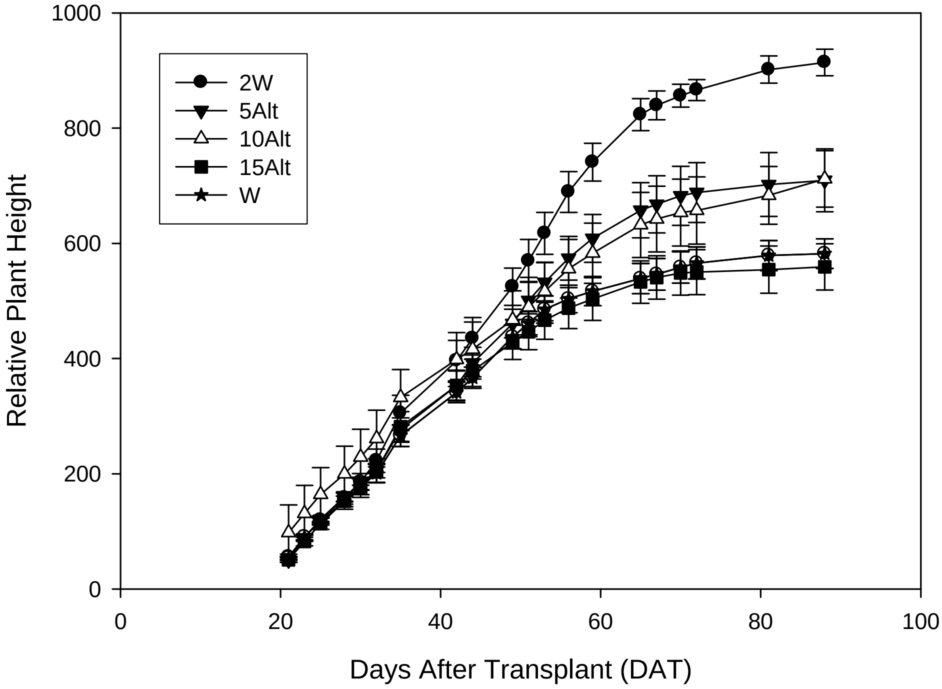


Figure 3.11 Effect of PRD alternation strategy on relative plant height in cotton (T2)

NB: Errors bars represent S.E. (n = 10)

Table 3.3 Effect of PRD alteration strategy on final leaf area in cotton (T2)

Treatment	Leaf Area (cm^2)	Final Plant Mass (g)	Water Applied (ml)	CWU (g/L)	S.E.
2W	4049.1 a	102.8	23319	4.41	0.36
5Alt	2966.9 b	84.8	17698	4.79	0.22
10Alt	2767.0 b	79.2	17405	4.55	0.28
15Alt	2849.6 b	85.3	16713	5.10	0.38
W	2657.7 b	70.6	14660	4.81	0.33

Figures followed by the same letter are not significantly different from each other (P = 0.01)
CWU = Crop Water Use (Plant Mass / Water Applied)

There was no significant difference in the number of fruiting branches measured between any of the treatments throughout the trial (data not shown). However, the trend in number of fruiting sites (Figure 3.12) throughout the trial was similar to that found for the plant heights. At 55 DAT (80 DAP), the Control (2W) plants had significantly more fruiting sites than the 10Alt, 15Alt and W plants but there were no other significant differences. At 58 DAT (83 DAP), the only significant difference was the Control 2W compared to the W treatment. By 69 DAT (94 DAP), 2W was significantly greater than 15Alt and W, with all other treatments being the same. By 71 DAT (96 DAP), 2W was significantly greater than all other treatments except 5Alt while all other treatments were not significantly different. There was no significant difference in retention rates throughout the trial (data not shown).

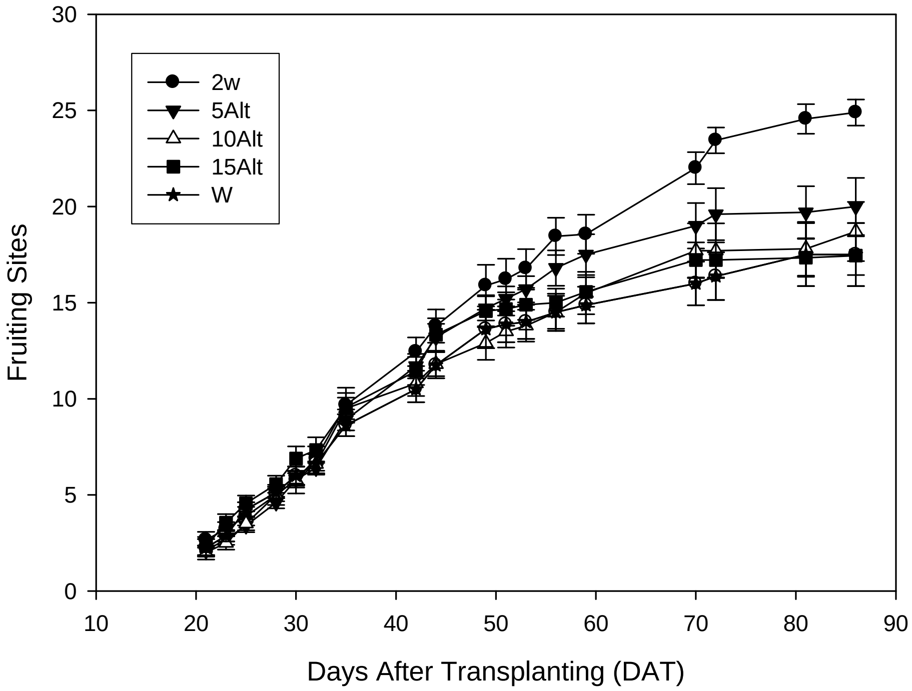


Figure 3.12 Effect of PRD alternation strategy in cotton on fruiting sites (T2)

NB: Error bars represent S.E (n = 10)

Trial 4 (T4)

The PRD16% treatment was alternated four times and the PRD10% and PRD10% plus 4 days treatments were alternated twice during the T4 trial (Figure 3.13). Volumetric soil moisture contents were observed to have a slightly decreasing trend throughout the experimental period for all treatments. For the well watered Control treatment, this decrease was approximately 3% and was presumably due to consolidation of the potting soil.

There was no significant difference in plant height between any of the T4 treatments applied (data not shown). However, there was a divergent trend in plant height developing with PRD deficit applied plants being shorter as the trial progressed (Figure 3.14). Final (80 DAT) total plant dry biomass was greater in the Control treatment compared to the other treatments which were not significantly (p = 0.05) different from each other (Table 3.4). A significant difference (P = 0.05) in crop water use productivity (grams dry weight/ litre of water applied) was present between the Control (2W) and all other treatments which were not significantly different from each other (Table 3.3).

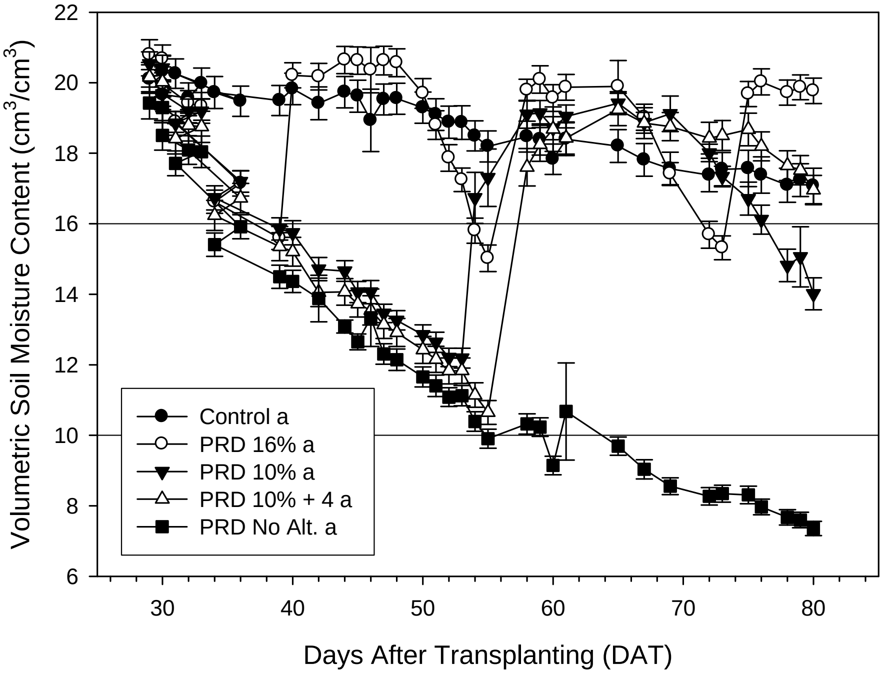
Table 3.4 Final average above ground plant dry mass (80 DAT) for various PRD alternation strategies in cotton (T4)

Treatment	Dry Mass (g)	S.E.	CWU (g/L)	S.E.
Control	45.7 a	1.3	2.23 a	0.051
PRD16%	39.1 b	1.0	2.86 b	0.079
PRD10%	39.0 b	1.6	2.96 b	0.057
PRD10% + 4	37.8 b	1.0	2.84 b	0.063
PRD No Alt	38.5 b	1.1	3.02 b	0.059

Figures followed by the same letter are not significantly different from each other (P = 0.05)
CWU = Crop Water Use (Plant Mass / Water Applied)

There was no difference in leaf area at 40 DAT except between the Control and non-alternated treatments (Table 3.5). At 50 DAT, the leaf area of the Control treatment was larger than all other treatments except the PRD10% + 4 treatment. However, the final leaf area measurement (80 DAT) showed a general trend of decreasing leaf area with PRD and/or general deficit applied. The leaf area in the Control, PRD10% and PRD16% treatments were not significantly different from each other but were larger than the PRD10% + 4 and the PRD No Alt treatments (Table 3.5).

(a)



(b)

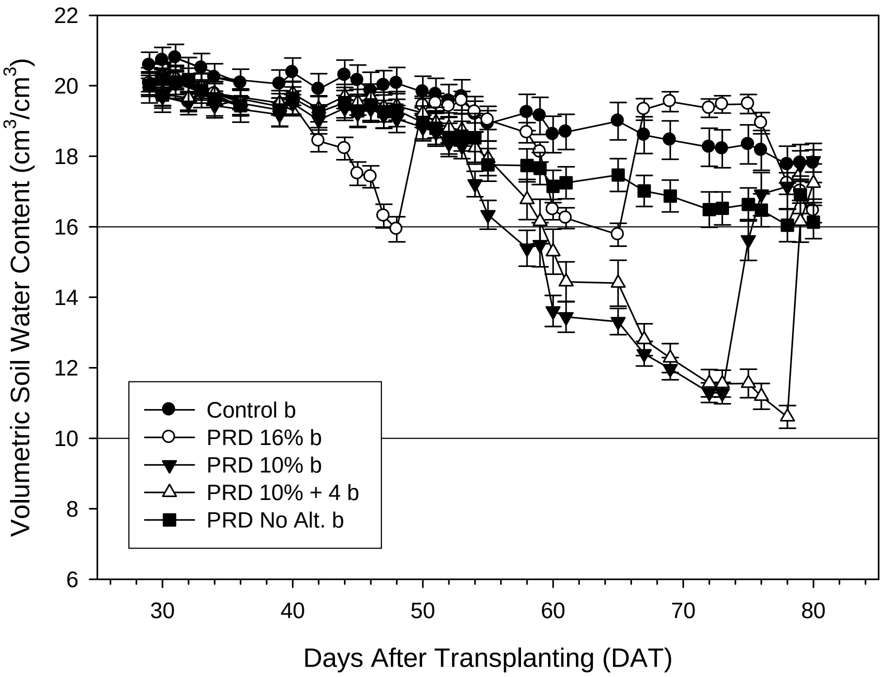


Figure 3.13 Volumetric soil moisture of (a) one side and (b) the other side of twin-pots planted with cotton under different PRD alternation strategies (T4)

NB: Error bars represent S.E

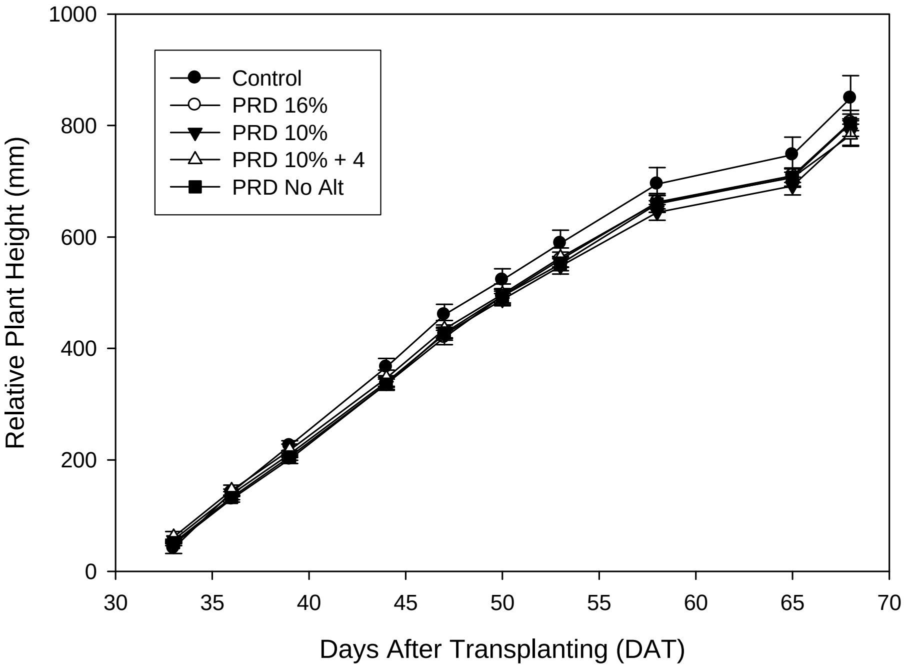


Figure 3.14 Effect of PRD alternation strategy on relative plant height of cotton (T4)

NB: Plant heights are less pre-treatment height, error bars represent S.E

Table 3.5 Effect of PRD alternation strategy on leaf area estimated at 40 and 50 DAP and measured at 80 DAT for cotton (T4)

Treatment	n	40 DAT	50 DAT	80 DAT
Control	8	2090.6 a	2868.0 a	3070.7 a
PRD16%	10	1868.3 ab	2564.3 b	2806.8 ab
PRD10%	10	1883.6 ab	2547.6 b	2800.8 ab
PRD10% + 4	10	1945.2 ab	2592.7 ab	2748.8 b
PRD No Alt.	10	1827.6 b	2488.9 b	2686.5 b

Figures followed by the same letter are not significantly different from each other (P = 0.05)

There was no significant difference in fruiting branches between the treatments (data not shown). However, the Control had significantly more fruiting sites than the non-alternated PRD and the PRD10% + 4 days treatments during the period from 47 to 58 DAT and 68 to 72 DAT (Figure 3.15). There was no significant difference in fruit retention rate between the treatments at any of the sampling dates (data not shown). However, the Control treatment consistently had the lowest retention rate followed by the PRD10% + 4 days treatment.

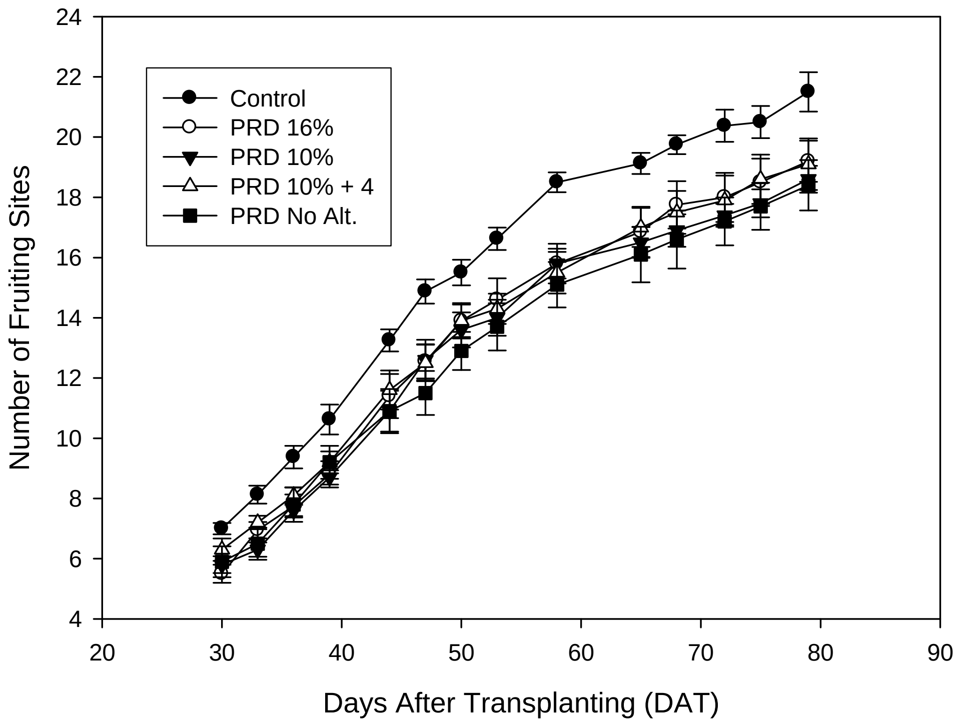


Figure 3.15 Effect of PRD alternation strategy on fruiting sites in cotton (T4)

NB: Error bars represent S.E

3.4 Discussion

3.4.1 Effect of Non-alternated PRD on Plant Growth

This preliminary trial was conducted to evaluate the effect on both water extraction and plant growth of the 'wet' side water deficit applied in a non-alternated PRD system. While the deficits imposed on the 'wet' side of the plant prior to irrigation were larger than targeted (Table 3.1), significant differences in soil moisture deficits consistent with the trial objectives were imposed across the treatments (Figure 3.2).

Soil moisture continued to be extracted from the 'dry' side of the root zone in each treatment throughout the trial and the soil water suction on the dry side exceeded the measurement range (>600 kPa) of the gypsum blocks in the 50 and 100 kPa treatments by the end of the trial (Figure 3.2). The lower soil suction values measured on the 'dry' side of the 200 kPa treatment after the 40 DAT irrigation suggests that there may have been some leakage around at least some of the plastic barriers in this treatment after this irrigation, and possibly at other times throughout the trial. Rehydration via transport through the roots from the 'wet' to 'dry' side could also be suggested as the cause. However, this is unlikely given the extent of soil moisture increase measured.

There was no significant difference between the treatments in either the rate of extraction, or level of maximum extraction, from the 'dry' root zone. However, the lack of a significant difference may have been affected by the relatively small number of replicates used as there was a trend towards greater 'dry' side extraction in the 100 kPa treatment compared with the 50 kPa treatment (Figure 3.2). This suggests that the rate of moisture extraction from the 'dry' areas of the root zone may be influenced by the moisture availability in the 'wet' root zone and that the extraction from the 'dry' areas increases as the soil suction of the 'wet' zone increases. However, the moisture content continued to decline in the 'dry' root zone after 40 DAT even when there was only low soil suction (i.e. 50 kPa) in the 'wet' zone. This may have been due to continued root extraction or soil drying under the glasshouse conditions.

Reducing the soil suction at which irrigation was applied was found to increase plant height (Figure 3.3) and is consistent with findings (e.g. Hearn 1994) which suggest that the first physiological process reduced by limited soil moisture is cellular expansion and vegetative growth. The indirect consequence of a lower vegetative growth rate and smaller leaf area is a reduction in total assimilate production capacity which reduces the number of fruiting branches (Figure 3.4) and fruiting sites (Figure 3.5) as well as the final dry mass (Table 3.2) of the plants experiencing higher moisture deficits. However, it is interesting to note that there was no significant difference in root mass between the treatments possibly due to a compensatory mechanism by which plants under higher moisture stress direct a greater proportion of their energy towards root growth.

It is only possible to directly evaluate PRD effects on plant growth by comparing the Control and 100 kPa treatments as these were irrigated at a similar deficit. The Control was found to be significantly taller (Figure 3.4) and have a significantly greater above ground plant mass (Table 3.2) than the 100 kPa non-alternated PRD treatment. There was no difference in fruiting branches or number of fruit sites despite a trend towards higher values in the Control treatment. This suggests that irrigating a restricted area of the root zone may influence plant growth. However, the same effect was observed due to the impact of increasing soil moisture deficit and it is possible that by reducing the irrigated volume of root zone that the plant is simply experiencing a moisture deficit. This may in turn reduce the plant's water status and turgor and could produce a growth response based on hydraulic drivers rather than the biochemical root signalling normally associated with PRD. Hence, this trial is inconclusive regarding the benefits of PRD in cotton as it is necessary to measure the plant water status and/or the plant's biochemical responses to root zone moisture differences to adequately separate the influence of moisture deficits and PRD signalling.

3.4.2 Effect of Non-alternated PRD on AbA Production

Xylem sap Abscisic Acid concentration ([AbA]) was found to vary significantly over time as soil moisture decreased in the non-alternated PRD treatment (Figure 3.8). This is consistent with previous work which identified a strong correlation between elevated xylem sap [AbA] and soil drying under PRD (Dry *et al.* 1996, Loveys *et al.* 2000, Loveys *et al.* 1998, Sobeih *et al.* 2004, Stoll, Loveys & Dry 2000). However, the presence of two peaks in AbA elevation during the trial has not been reported elsewhere. The first AbA elevation and subsequent decline occurred at a relatively low soil moisture deficit of 271 to 354 kPa and may be a response induced by the drying of roots which had grown into the Geofabric® lining in the bottom of each pot (Appendix B). When the water was removed from the saucers below the pots on trial initiation, roots in the Geofabric® would have dried rapidly potentially causing the elevated synthesis and release of AbA. The second AbA peak in the non-alternated PRD treatment occurred after 15 days and coincided with a volumetric soil moisture level of 11.6% (i.e. approximately 2360 kPa). This would seem to be the more realistic AbA elevation response in cotton to PRD soil conditions as it coincided with a soil water deficit similar to that found in previous studies (Dry *et al.* 1996, Loveys *et al.* 2000, Loveys *et al.* 1998, Sobeih *et al.* 2004, Stoll, Loveys & Dry 2000).

The elevation of xylem sap [AbA] under PRD has been found (Dry *et al.* 1996, Loveys, Stoll & Dry 2001, Loveys *et al.* 1998, Stoll, Loveys & Dry 2000) to cause a partial reduction in stomatal aperture under conditions were plant water status has been maintained. However, in this trial the non-alternated PRD treatment produced a four fold elevation of stem sap [AbA] (Figure 3.8) but did not reduce stomatal conductance (Figure 3.9). Stem water potential was maintained in the non-alternated PRD treatment up until 21 DAT (Figure 3.7) confirming that up until this time there was no deficit effect on plant growth. The small but significant reduction in stem water potential in the PRD treatment at 21 DAT may have reflected the difference in plant size by this date, the difficulty in maintaining moisture extraction rates from small root volumes and/or due to the increase sample number.

The lack of a stomatal response in the non-alternated PRD treatment raises doubts over the sensitivity of cotton to [AbA] and the potential to obtain water use productivity benefits from PRD strategies in this crop. However, several factors may have dampened the measured stomatal response and care should be exercised when drawing conclusions over whether or not increases in xylem-borne AbA concentrations are adequate to explain observed changes in stomatal behaviour (Wilkinson & Davies 1997).

Stomatal conductance responds to both the immediate external environment of the leaf ([CO_2], partial pressure, temperature and irradiance) as well as hydraulic and chemical changes in the internal leaf status (Dodd 2003, Gutschick 2002). This trial was conducted under comparatively low evaporative conditions within a glasshouse environment which may have reduced the transport of AbA to, and the sensitivity of, stomata (Gutschick 2002, Radin 1992, Trejo, Clephan & Davies 1995, Wilkinson & Davies 2002). Similarly, the [AbA] was measured in the stem sap and this may not accurately reflect the leaf [AbA] present (Wilkinson & Davies 1997). The [AbA] in the leaf apoplast (site of action) is influenced by the sequestration and release of AbA by the symplast and metabolism by mesophyll cells (Radin 1992, Trejo, Clephan & Davies 1995, Trejo, Davies & Ruiz 1993, Wilkinson & Davies 2002). Hence, the increase in xylem [AbA] may not have been sufficient to produce changes in stomatal behaviour (Wilkinson & Davies 1997). Even where stomata responses are correlated to changes in xylem sap [AbA], the xylem sap AbA may not contribute substantially to leaf [AbA] and there may be other factors (e.g. sap alkalinisation) which cause the stomatal response (Wilkinson & Davies 1997, Zhang & Davies 1990). For example, sap pH appears to modulate AbA action in the leaf probably by changing the degree of ionisation of AbA and thus its ability to move freely in the apoplast (Gutschick 2002, Wilkinson & Davies 1997). Hence, factors including species specific metabolic activity (e.g. metabolism, compartmentation of AbA, sap alkalinity) should also be considered when investigating the response of stomata to xylem sap AbA (Dodd 2003, Holbrook *et al.* 2002, Wilkinson & Davies 1997).

A chemical based root signal provides the plant with a means to sense the conditions of water extraction (i.e. soil water status and resistance to water flux) on a daily timescale. A short-term plant response to this chemical signal would vary greatly as a function of concentration of hormone in the xylem and the delivery rate which is influenced by the water flux, evaporative demand and leaf water potential (Davies & Jones 1991, Tardieu, Zhang & Gowing 1993, Trejo, Clephan & Davies 1995). Under the glasshouse conditions imposed, the soil moisture conditions were conducive to elevate [AbA] in the xylem sap, but the low evaporative conditions imposed and lack of xylem sap alkalinisation may have been responsible for sufficient metabolism, sequestration and compartmentation of AbA to stop a stomatal response from occurring. The low evaporative conditions may have also limited transpirational flux and the lack of sap alkalinisation may have inhibited the delivery of elevated levels of [AbA] to guard cells in sufficient quantities to cause an overload of mesophyll based AbA metabolism and/or reduced the mesophyll metabolism capacity (Trejo, Clephan & Davies 1995, Wilkinson & Davies 1997).

Wilkinson and Davies (1997) found that an increase in apoplastic [AbA] may be responsible for the reduction in stomatal conductance due to a reduction in the normal, rapid symplastic sequestration away from the apoplast due to alkalinisation and/or a release of AbA trapped in the cytosol of leaves (Davies & Jones 1991). The anisohydric and low stomatal response of cotton (Lacape, Wery & Annerose 1998, Percy, Lu & Radin 1996) has been found (Li, Xu & Cohen 2005, Meron *et al.* 1987, Tardieu & Simmonneau 1998) to produce a decrease in leaf water potential under high evaporative conditions and limited soil moisture availability. This may also explain the lack of stomatal response in this trial but highlights the difficulties faced in measuring physiological responses to PRD in cotton.

3.4.3 Effect of Alternated PRD on Plant Growth

The application of alternated PRD strategies was generally found to reduce both vegetative (i.e. height, leaf area) and reproductive (i.e. fruiting sites) plant growth indicators compared to Control treatments irrigated on both sides of the plant (e.g. Figures 3.11, 3.12 & 3.16; Tables 3.3 & 3.4). Increasing the period between PRD alternations from 5 to 15 days when the soil moisture potential in the wet root zone was maintained between 30 and 60 kPa also reduced the plant height (Figure 3.11) and the number of fruiting sites (Figure 3.12). However, where the soil moisture in the wetted root zone was maintained at <3 kPa (T4) and alternation was based on the dry root zone moisture levels 16% (~350kPa) and 10% (>1500kPa) there was no difference in the major plant growth indicators (i.e. height, fruiting branches, fruiting sites, leaf area) between the various alternated PRD treatments (e.g. Figures 3.15 & 3.16; Table 3.4). As the treatments in the T4 trial were variously alternated between 2 and 4 times, this suggests that the level of moisture availability in the wet root zone area is a key factor influencing water uptake and crop stress under alternated PRD conditions.

Destructive plant sampling would have been required to measure plant water status on these trials. As this was not possible, there is insufficient data to conclusively separate physiological differences associated with PRD root signalling from those associated with reduced water availability (i.e. deficit irrigation). However, in a practical sense it is impossible to supply the soil water at a smaller potential than that applied in T4 (i.e. < 3 kPa) and the lack of differences in the main plant growth measurements across the T4 PRD treatments suggests that plant water status was maintained in these plants irrespective of the alternation strategy.

Where the soil moisture in the wet root zone was maintained between 30 and 60 kPa (T2) there was no difference in plant height and number of fruiting sites up until 69 DAT. However, after 69 DAT, the Control treatment was taller with more fruiting sites than the alternated PRD treatments while there was no difference between the 15Alt and W treatments. This suggests that at least some of the growth differences in the T2 trial may be related to moisture stress, presumably due to the smaller wetted root zone of the alternated PRD treatments being unable to supply the same rate of water uptake as the Control treatment wetted on both sides of the plant. The lack of a difference between the 15Alt and W (i.e. non-alternated PRD) treatments suggests that the 15 day alternation interval did not produce a root signal that influenced plant growth and that the growth differences observed in this trial may be more closely linked to deficit effects than PRD root signalling. Hence, differences between the T2 treatments may be at least partially attributed to hydraulic forces and chemical signalling (Munns *et al.* 2000) associated with a form of deficit irrigation rather than due solely to increased AbA production and root signalling arising from the implementation of alternated PRD. This is further supported by the significant improvement in crop water use productivity of the partially wetted (alternated and non-alternated PRD) treatments compared to the well watered Control. Although this in some respects may also be attributed to the artefacts of the Control treatment being prone to greater losses due to evaporation from the soil surface in T2 and shallow water table (saucer beneath each pot) in T4.

3.5 Conclusions

A series of glasshouse trials have been conducted to evaluate the plant growth and physiological responses of cotton to various deficit irrigation strategies including both non-alternated and alternated PRD. There was no difference in either the rate of moisture extraction or maximum soil water potential reached in the dry root zone area when the soil moisture in a non-alternated wet root zone area was varied between field capacity and 250 kPa. However, increasing soil moisture deficit in the wet root zone area reduced plant height, above ground plant mass and the number or fruiting branches and sites.

Drying a proportion of the root zone was found to produce an elevated xylem stem [AbA] when the dry portion of the root zone was at a soil moisture potential of >1500 kPa (i.e. 15 days after irrigation withheld in a heavy clay soil). However, applying non-alternated drying to only a portion of the root zone did not have any effect on stem sap pH, stem water potential or stomatal conductance under the comparatively low evaporative conditions present in the glasshouse.

The application of alternated PRD strategies generally resulted in reduced plant growth (i.e. plant height, fruiting sites, plant mass, leaf area) compared to a Control watered on both sides of the plant. There was no effect of PRD alternation strategy on plant growth where a low (i.e. < 3 kPa) soil moisture potential was supplied to the wet root zone area. However, when the moisture in the wetted root zone was maintained between 30 and 60 kPa increasing the PRD alternation period from 5 to 15 days reduced plant growth and the number of fruiting sites with the effect increasing with plant age (i.e. size). This response was similar to that observed under deficit irrigation producing improved crop water use productivity, however, it may have been an artefact of the limited rooting volume and water uptake capacity associated with the pot trial.

Further trial work is required to evaluate PRD under field conditions. The higher evaporative demands typically experienced under field conditions may influence the stomatal conductance response to AbA signalling. Similarly, the potentially larger root volume may be expected to influence the rate of water uptake and improve the ability to separate moisture deficit effects from PRD root signalling responses. However, the application of alternated PRD strategies under field conditions are also expected to raise a number of pragmatic difficulties associated with maintaining defined wet and dry root zone areas at the moisture deficits identified as necessary in the glasshouse studies.

Additional future trials which could be conducted to confirm the presence of PRD signalling and the benefits of alternative PRD strategies in cotton should consider using a larger number of plants to enable destructive sampling for leaf and xylem sap [AbA], sap pH and stem water potential. The trials should also be conducted in a controlled environment with field comparable climatic conditions (e.g radiation, vapour pressure deficit and temperature). This is necessary, as the higher evaporative conditions experienced in the field would be expected to increase the transpiration flux and therefore delivery rate of AbA to the guard cells. This could potentially change both the rate of compartmentation, sequestration and metabolism of AbA by mesophyll cells and the sensitivity of the stomatal responses to [AbA]. Diurnal measurements of [AbA] in the xylem stem sap and in the leaf and sap pH may also be desirable as [AbA] delivery to sites of action is linked with soil moisture extraction and transpiration flux and has a circadian rhythm (Munns *et al.* 2000). This would allow a better matching of any stomatal conductance response to measured changes in [AbA] and sap pH.

4.0 FIELD EVALUATION OF PARTIAL ROOTZONE DRYING AND DEFICIT IRRIGATION IN COTTON

4.1 Introduction

A mild moisture stress is desirable in cotton production to maximize yield and prevent a delayed maturity and excessive vegetative growth (Hearn & Constable 1984). Glasshouse evaluations of partial rootzone drying and regulated deficit irrigation strategies (Chapter 3) identified a range of impacts on physiological growth associated with moisture stress. However, there has been little field research conducted into the benefits and limitations of either deficit or PRD irrigation techniques in cotton in Australia. This has been due to the prevalence of surface irrigation application systems, which do not easily lend themselves to the implementation of PRD or DI strategies. However, these strategies can be easily applied under large mobile irrigation machines (LMIMs). As the area of crop grown LMIMs is forecast to increase (Foley & Raine 2001), investigations into the benefits and limitations associated with the implementation of PRD or DI strategy using LMIMs operating under commercial conditions is warranted. Hence, this chapter reports on field trials conducted to evaluate both the ability to apply PRD and DI strategies, and the effect on the growth and yield of cotton, using commercial centre pivot and lateral move irrigation machines.

4.2 Methodology

Field trials to evaluate the benefits of deficit irrigation and PRD were conducted during the 2002/2003 and 2003/2004 cotton seasons. Soil moisture, plant and harvest yield measurements were collected to assess the effect of various DI and PRD strategies on soil-water movement, plant growth, yield and water use productivity.

4.2.1 Trial Location and Irrigation Application System

2002/2003 Season

The 2002/2003 field trial was conducted on 'Macquarie Downs' (S270 54.176', E1510 30.871), located between Leyburn and Millmerran on the eastern Darling Downs, Queensland. The trial area encompassed approximately 4.3 ha of commercial cotton (variety - Sicot 80) grown on a black cracking clay (Vertosol) soil with the plant being planted on a one metre row spacing. The irrigation treatments were located beneath one span of a Valley (Valmont Industries, Omaha, Nebraska) lateral move irrigation machine. The span used for the field trial was fitted with three custom made water manifolds to enable the precise regulation and alternation of irrigation applications (Plate 4.1). Each manifold was slung beneath the span and provided water via pressure regulators, electric control solenoids and different sized nozzles to a series of low energy precision application (LEPA) socks. The LEPA socks delivered the water at the ground surface in the middle of every second furrow (Plate 4.2). Seven different discharge rates could be applied in each furrow by controlling which nozzles were discharging at any point in time. To enable the application of different PRD alternation strategies, an electric motor driven cable was attached to the water manifold (Plate 4.3). This cable moved the manifold a horizontal distance of one metre to enable the LEPA socks to re-align with the middle of the previously dry furrow. A programmable logic controller (PLC) connected to the water supply solenoids and electric motor driven cable controlled the application of the various PRD and deficit irrigation treatments (Plate 4.4). Position in the field and switching between irrigation treatments by the PLC was controlled by a micro switch mounted on the irrigator cart (Plate 4.5a). The micro switch was activated as it came into contact with a 20 litre drum positioned at the start of each plot and evenly spaced along the travel path of the machine (Plate 4.5b).


Plate 4.1 Water manifold used to control the volume of water applied to the irrigation treatments


Plate 4.2 LEPA socks delivering irrigation water to the soil surface in every 2nd furrow

Plate 4.3 Linear actuators and pulley arrangements used to alternate which furrow is being irrigated

Plate 4.4 Programmable logic controller used to control the irrigation application treatments

(a) **(b)**

Plate 4.5 (a) Micro-switch mounted on the irrigation cart and (b) row of 20L drums positioned down the field to trigger the PLC to alternative irrigation treatments

2003/2004 Season

The 2003-2004 field trial was conducted on 'Rainbow Valley' (S 27^0 22.612", E 151^0 37.412"), located adjacent to Doctors Creek, 13 km west of Oakey, Queensland. The trial encompassed approximately 1.2 ha of commercial cotton (variety - Sicot 71) grown on a black cracking clay (Vertosol) soil. The trial was located beneath one span of a Lindsay Zimmatic (Omaha, NE) centre pivot irrigation machine. The span used for the trial was fitted with the same water manifold and irrigation control infrastructure as for the 2002/2003 trial.

4.2.2 Trial Design and Management

2002/2003 Season

This field trial was conducted to evaluate a range of both deficit and PRD irrigation strategies under commercial conditions. The trial was laid out as a row/column design, consisting of three treatment columns by fifteen rows. The 45 plots were separated into three blocks (i.e. 15 plots each) along the travel direction of the machine (Figure 4.1). Each plot area was eight crop rows (i.e. 8 metres) wide and approximately 52 m in length. Each of the three treatment columns were separated by a buffer of eight crop rows managed using commercial practice.

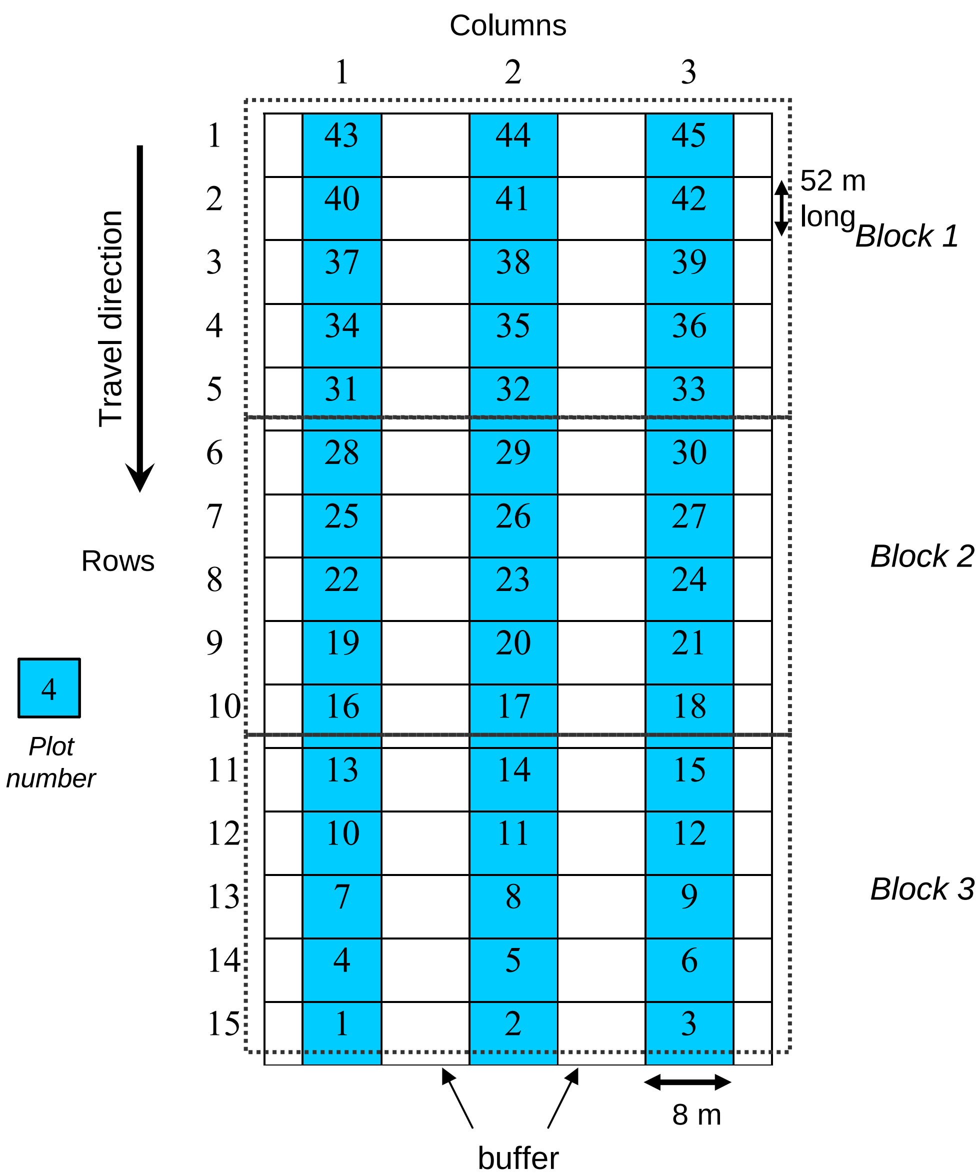


Figure 4.1 Field plot layout (not to scale) under the lateral move irrigation machine, 'Macquarie Downs' (2002/2003)

Five deficit irrigation treatments (25, 50, 75, 100 and 125% of normal commercial practice) were overlaid with three PRD alternation treatments (no alternation, alternated after second irrigation and alternated after fourth irrigation) which were randomly assigned to the 15 plots in each block. However, due to in-crop rainfall, only two PRD alternation treatments (no alternation and alternated after second irrigation) were able to be applied. Hence, there were 10 treatments applied (Table 4.1).

Table 4.1 Deficit and PRD irrigation treatments, Macquarie Downs (2002/2003)

PRD alternation strategy	Volume of irrigation applied (% of commercial application)	Treatment label
Water applied one side of the plant and not alternated	25	25Non-alt
	50	50Non-alt
	75	75Non-alt
	100	100Non-alt
	125	125Non-alt
Water applied to one side of plant and alternated after second irrigation	25	25Alt
	50	50Alt
	75	75Alt
	100	100Alt
	125	125Alt

The crop was planted on the 25th October 2002 after a pre-irrigation of 98 mm was applied. The trial area was thinned to a uniform stand within the first three weeks of emergence. Rainfall throughout the season was measured using an on-farm rain gauge while temperature data was obtained from a local Bureau of Meteorology weather station (Figure 4.2). Total in-crop rainfall was 298 mm. Approximately 105 mm of rain fell during the October to December period which delayed the first in-season irrigation event until the 13/1/03 (80 DAP- flowering). This crop was harvested on the 1st May 2003. Potential evapotranspiration (ET) during the season was estimated as 740 mm using the Penman-Monteith method in Watershed® Version 3.0 (QDPI&F, Toowoomba).

Four irrigation events were applied during the trial period with the PRD alternation applied to the third irrigation event (Table 4.2). A total of 210 mm was applied in the commercial irrigation. The deficit treatments, which were applied as percentages of the commercial irrigation volumes, ranged from 71 to 100% potential ET replacement (Table 4.3).

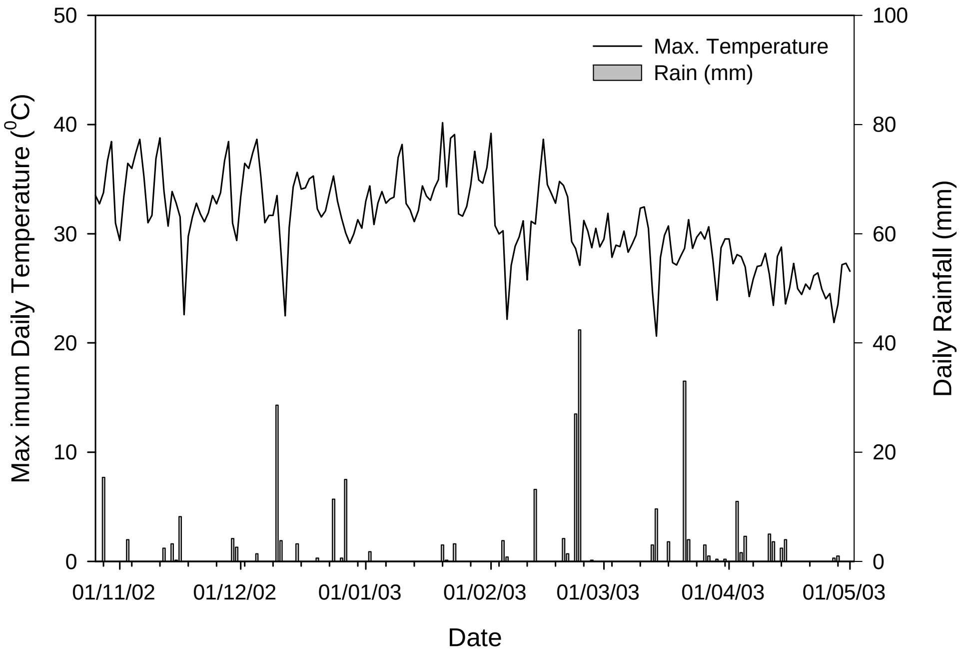


Figure 4.2 Rainfall and temperature during the irrigation trial, 'Macquarie Downs' (2002/2003)

Table 4.2 Commercial irrigations applied, 'Macquarie Downs' (2002/2003)

Irrigation	Date	DAP[A]	Crop growth stage	Irrigation volume applied
1	13/1/2003	80	Flowering	56 mm
2	19/1/2003	86	Flowering	56 mm
3	22/1/2003	89	Flowering	61 mm
4	10/2/2003	108	Flowering	37 mm

[A] Days after planting

Table 4.3 Potential evapotranspiration replaced by irrigation applications, 'Macquarie Downs' (2002/2003)

Irrigation treatments (% commercial applied volume)	**Potential evapotranspiration replaced** [A]
25%	71%
50%	79%
75%	86%
100%	93%
125%	100%

[A] ET estimated using Penman-Monteith equation

2003/2004 Season

The 2003/2004 trial investigated the effect of both deficit irrigation and PRD alternation strategies. It was laid out in a similar row/column design as the 2002/2003 season trial. However, in this case the treatment plots varied in length from 30-36 m due to the circular movement of the centre pivot machine. The trial was designed with three deficit irrigation treatments (75%, 100% & 125% of commercial practice) overlaid with five PRD alternation strategies (non-alternated, alternated every irrigation, alternated every second irrigation, alternated every third irrigation and alternated every fourth irrigation). These treatments were randomly assigned to the 15 plots in each of the three blocks as per the 2002/2003 trial. However, due to in-crop rainfall only three of the PRD treatments (non-alternated, alternated every irrigation, alternated every second irrigation) were applied. Hence, in total there were nine treatments applied (Table 4.4).

Table 4.4 Irrigation treatment applied, 'Rainbow Valley' (2003/2004)

PRD Alternation strategy	**Volume of irrigation applied** (% of commercial application)	**Treatment label**
Water applied one side of the plant and not alternated	75	75% Non-alt.
	100	100% Non-alt.
	125	125% Non-alt.
Water applied to one side of plant and alternated after every irrigation	75	75% Alt. every
	100	100% Alt. every
	125	125% Alt. every
Water applied to one side of plant and alternated after second irrigation	75	75% Alt. 2nd
	100	100% Alt. 2nd
	125	125% Alt. 2nd

The crop was planted on the 29th and 30th October 2003 and irrigated up with a 10 mm irrigation. Rainfall was measured using an on-farm rain gauge and temperature obtained from a nearby Bureau of Meteorology weather station (Figure 4.3). Total in-crop rainfall was 495 mm and potential ET was 910 mm calculated using the Penman-Monteith method in Watershed® Version 3.0 (QDPI&F, Toowoomba)..

A total of 120 mm was applied by the three commercial irrigations conducted during the trial period (Table 4.5). A total of 155 mm of rain fell in-crop before the first irrigation event (63 DAP) and 245 mm of rain fell between the second and third irrigation events. A further 120 mm of irrigation was applied with over-crop sprinklers after the crop had cut out. The evapotranspiration replaced by the irrigation treatments ranged from 77.5% to 84.1% potential ET (Table 4.6).

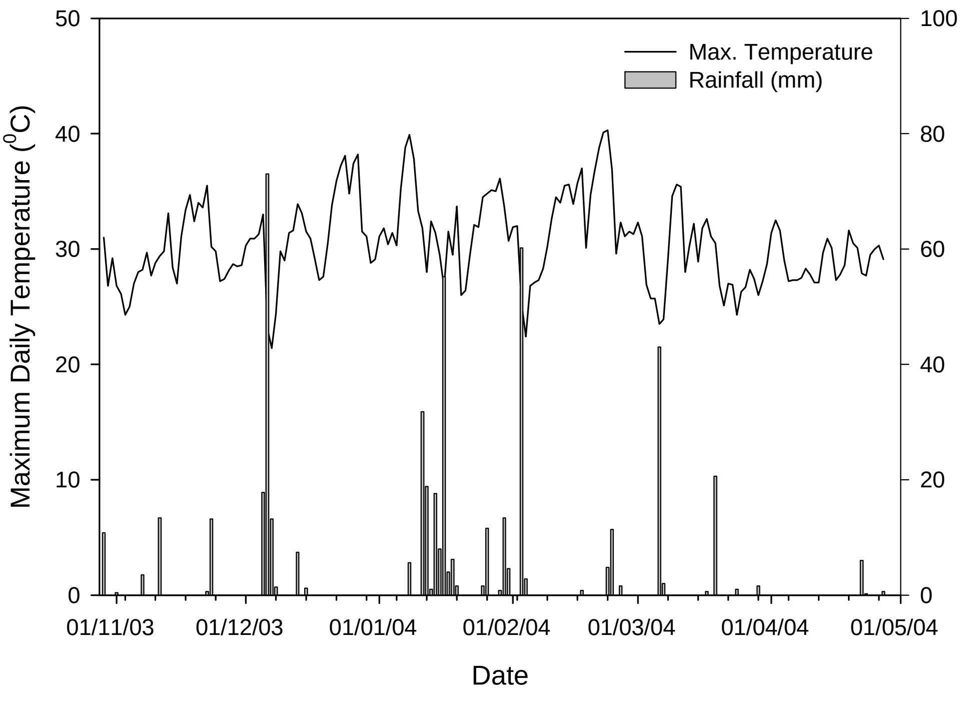


Figure 4.3 Rainfall and temperature during the irrigation trial, 'Rainbow Valley' (2003/2004)

Table 4.5 Commercial irrigations applied, 'Rainbow Valley' (2003/2004)

Irrigation	Date	DAP[A]	Crop growth stage	Irrigation volume applied
1	31/12/2003	63	Squaring	40 mm
2	7/1/2004	70	Flowering	40 mm
3	15/2/2004	109	Flowering	40 mm

[A] Days after planting

Table 4. 6 Potential evapotranspiration for irrigation treatments, 'Rainbow Valley' (2003/2004)

Irrigation treatments (% commercial applied volume)	**Potential evapotranspiration replaced** [A]
75%	77.5%
100%	80.8%
125%	84.1%

[A] ET estimated using Penman-Monteith equation and based on commercial applied volume

4.2.3 Soil Moisture Monitoring

2002/2003 Season

A total of 88 neutron moisture meter access tubes were installed across the DI and PRD treatments in 2002-03. Neutron moisture meter (NMM) tubes were installed across row 4 in the designated plots. Tubes were located in (a) the centre of the furrow each side of row 4, (b) half way between the furrow and crop row and (c) 16.5 cm from the plant row (Figure 4.4). Tubes were offset to avoid measurement interference from neighbouring tubes. NMM readings were taken to a depth of 1.2 metres measured at 10 cm increments. The top 15cm of soil moisture was measured by calibrated ThetaProbe® (Delta-T Devices Ltd, UK).

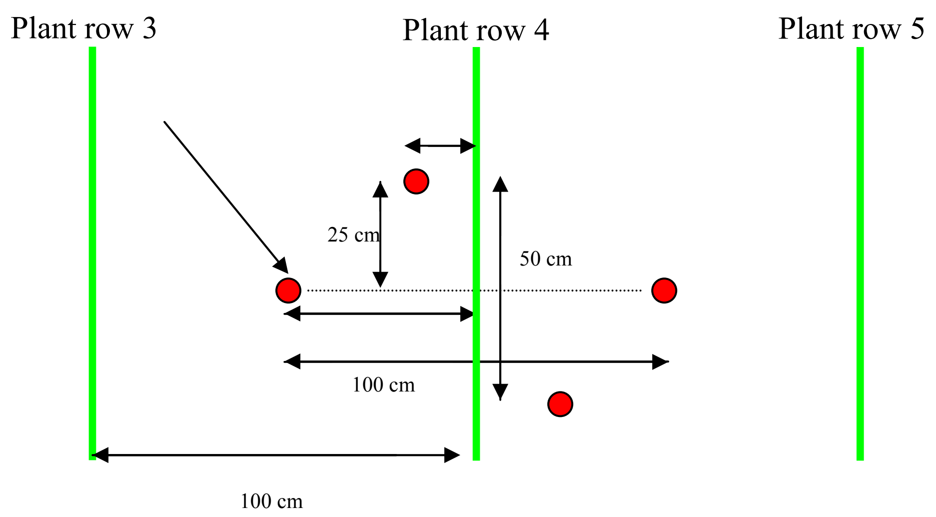


Figure 4.4 Location of neutron moisture meter access tubes

2003/2004 Season

A total of 60 neutron probe tubes were installed in 2003/2004 across all PRD treatments receiving the lowest DI treatment. NMM readings were taken to a depth of 1.2 metres. A site specific NMM calibration curve was developed by sampling for gravimetric moisture content and bulk density from soil samples collected during neutron moisture meter access tube installation.

The volumetric soil moisture content values obtained by neutron moderation were used to create soil moisture contour maps using Surfer® Version 6.4.0.27 (Golden Software, Inc. Colorado, USA) across the plant row as a visual guide to identifying the soil moisture gradients achieved for a selected number of plots encompassing the range of irrigation depths and alternation treatments applied.

4.2.4 Plant Measurements

2002/2003 Season

Eight representative plants in each plot were tagged (four plants in both the 3rd and 6th row) and plant measurements (i.e. plant height, plant width, vegetative branches, fruiting branches, 4th-5th inter-node length and nodes above white flower) were collected from these plants on the 16/1/03, 21/1/03, 29/1/03, 7/2/03, 18/2/03 and 24/2/03 (i.e. 83, 88, 96, 105, 116, 181 DAP, respectively). Plants found to be tipped out had their tags moved to a neighbouring plant of similar growth.

Three destructive plant cuts were conducted on the 8/1/03, 4/2/03 and 27/2/03 (i.e. 75, 102 and 125 DAP, respectively). Plant cuts involved removing all plants in a one metre row length. The plant cuts undertaken on the 8/1/03 were used to evaluate correlations between leaf area, plant height and shading (measured with a ceptometre at 90^0 between the two harvest rows).

A total of six hand harvests were conducted after the first open bolls were matured. A two metre section of plants in the middle two rows of each plot were selected for each harvest (Appendix C). Harvests were conducted at 139, 146, 151, 165, 173 and 188 DAP. All harvested cotton was oven dried at 32^0C for 24 hours before dry boll weight and boll numbers were recorded. Conversion of lint weight to bales/ha assumed nominal 40% gin turnout and 20% picker losses.

Final plant fruit retention rate was measured for eight plants in each plot at 189 DAP (i.e. after the final hand harvest). The number of fruiting sites on each branch (vegetative and reproductive) and the presence or absence of the fruiting structure was recorded enabling the calculation of the total number of fruiting sites and retention rates.

2003/2004 Season

Five representative plants were tagged in row four of each plot and plant measurements (i.e. vegetative branches, fruiting branches, 4^{th}-5^{th} inter-node length, nodes above white flower and plant mapping for fruiting sites) were obtained for these plants on the 30/12/03, 22/1/04, 15/2/04 and 3/3/04 (i.e. 62DAP ~ squaring, 85DAP ~ first flower, 109DAP ~ mid-season and 126DAP ~ boll opening).

Four destructive plant cuts were conducted on the 3/1/04, 7/1/04, 18/2/04 and 11/3/04 (i.e. 66, 70, 112 and 134 DAP, respectively). Both leaf weight and leaf area was measured on a sub-sample from each plant cut and used to develop a relationship for estimating leaf area based on leaf weight for the remaining plant cuts.

A total of five hand harvests were conducted after the first open bolls had matured. In each case, a 2 x 2 metre section in the middle two rows of each plot was selected for harvest (Appendix D). Harvests were conducted at 153, 159, 169, 176 and 181 DAP. All harvested cotton was oven dried at 32^0C for 24 hours before dry cotton seed lint weight and boll numbers were recorded. Conversion of lint weight to bales/ha assumed nominal 40% gin turnout and 20% picker losses.

4.2.5 Statistical Analysis

Before analysis, all data sets were tested for compliance with the underlying ANOVA assumptions. Data sets found to violate the ANOVA assumption of normality were transformed to improve the symmetry of the distribution prior to analyses. Levene's test for homogeneity was used to test the equal variance assumption. Where Levene's test found heterogeneity, and the ratio of the largest to smallest sample standard deviation was less than two, the data set was considered suitable for ANOVA. If the ratio of the largest to smallest sample standard deviation exceeded two, the *P = 0.01* significance level was used to limit the occurrence of Type 1 errors. Unless otherwise stated, the level of significance was tested at P = 0.05.

Data analysis was conducted in SPSS for windows (version 11.5.0 and 12.0.1). Plant and yield data was analysed using the analysis of variance (ANOVA) mixed model approach. Pre-treatment measurement values were used as covariates. Row and column were also considered as covariate random effects in the mixed model. Tukey (Post-hoc, multiple pairwise comparison) tests were used to identify significant differences between individual treatments

4.3 Results

4.3.1 Soil Moisture

2002/2003 Season

Investigation of soil moisture measured on 9/1/2003 (prior to any irrigation treatments applied) across all plots containing neutron moisture meter access tubes found the average soil moisture to a depth of 130 cm was 459 mm with a standard deviation of 18 mm (n = 27). Measurements between neighbouring furrows on each side of the plant line prior to the application of any irrigations showed an average difference of 22.6 mm with a standard deviation of 12.8 mm (n= 27)

There was no significant difference in soil moisture for each of the treatments on the 9/01/2003 (i.e. 4 days prior to 1st irrigation event) and on the 19/01/2003 (i.e. prior to 2nd irrigation event) (Table 4.7). However, except for the lowest DI treatment

(25%), there was a trend of increasing soil moisture with increased water application on the 19/01/2003. There was a significant difference in soil moisture between the DI treatments on the 23/01/2003 (i.e. 1 day after the 3rd irrigation event) and an increasing trend in soil moisture with volume applied. This trend, although not significant, was also present on the 10/02/2003 (prior to the 4th irrigation event).

Table 4.7 Average root zone soil moisture content (mm) for the DI treatments, 'Macquarie Downs' (2002/2003)

DI Treatment	9/01/2003^A	19/01/2003^B	23/01/2003^C	10/02/2003^D
25%	461.9 a	451.6 a	438.8 a	428.8 a
50%	454.5 a	432.1 a	501.0 ab	447.8 a
75%	453.5 a	451.7 a	495.5 ab	461.8 a
100%	461.8 a	469.8 a	505.5 ab	467.0 a
125%	472.2 a	491.5 a	544.0 b	495.5 a

^A prior to any irrigation applied (P = 0.05), ^B prior to 2nd irrigation event (P = 0.05), ^C after 3rd irrigation event (P = 0.01), ^D prior to 4th irrigation event (P = 0.05)
Figures followed by the same letter are not significantly different from each other within columns

Comparison of soil moisture between neighbouring wet and dry furrows for each of the DI treatments (Table 4.8) found no significant difference on the 9/01/2003 (i.e. prior to the 1st irrigation event) and on the 19/01/2003 (i.e. prior to the 2nd irrigation event). On the 23/01/2003 (i.e. 1 day after the 3rd irrigation) there was a significantly larger soil moisture difference in the 25% treatment compared to the 50, 75 and 125% irrigation treatments. However, there was no distinct trend with irrigation water applied across the other treatments. There was also no significant difference in

Table 4.8 Differences in soil moisture content (mm) measured between neighbouring furrows for the DI treatments, 'Macquarie Downs' (2002/2003)

Treatment	9/01/2003^A	19/01/2003^B	23/01/2003^C	10/02/2003^D	18/02/2003^E
25%	30.4 a	39.5 a	79.3 a	36.3 a	35.6 a
50%	29.9 a	40.9 a	31.9 b	35.6 a	24.5 a
75%	31.4 a	37.8 a	29.6 b	20.0 a	22.8 a
100%	23.7 a	43.7 a	52.2 ab	48.0 a	23.0 a
125%	16.3 a	32.0 a	23.8 b	20.5 a	26.1 a

^A Prior to any irrigation applied (P = 0.05), ^B Prior to 2nd irrigation event (P = 0.05), ^C After 3rd irrigation event (P = 0.01), ^D Prior to 4th irrigation event (P = 0.01), ^E After 4th irrigation event (P = 0.05).
Figures followed by the same letter are not significantly different from each other (P = 0.05)

soil moisture between neighbouring furrows for any of the DI treatments on the 10/02/2003 (i.e. prior to the application of the 4th irrigation event) or on the 18/02/2003 (i.e 8 days after the 4th irrigation event).

There were no significant interactions in soil moisture content in the wetted furrow or gradient across neighbouring furrows found between PRD and DI treatments measured on the 23/01/2003 (i.e. after the 3rd irrigation event which was the 1st alternation event), on the 10/02/3003 (i.e. prior to the 4th irrigation event/ 2nd alternation event) or on the 18/02/2003 (i.e. 8 days after the 4th irrigation event) (Table 4.9). Although there was a high degree of variance for each treatment, there was a casual trend showing a reduction in soil moisture gradient with increased irrigation volumes applied. There was no trend in soil moisture gradient when comparing the non-alternated to alternated treatments with equal volumes of water applied. The variability in soil moisture was found to be greatest in the smaller irrigation treatments (data not shown).

Table 4.9 Wet furrow soil moisture content (Wet) and the difference in soil moisture content (mm) measured between neighbouring furrows (Gradient) for the PRD and DI irrigation treatments, 'Macquarie Downs' (2002/2003)

	23/01/2003[A]		10/02/2003[B]		18/02/2003[C]	
Treatment	Wet	Gradient	Wet	Gradient	Wet	Gradient
25Non-alt	472.9	51.0	396.5	40.5	413.5	30.2
50Non-alt	521.1	28.7	472.7	52.0	496.9	37.6
75Non-alt	514.6	22.5	470.0	34.5	499.4	23.1
100Non-alt	515.39	42.0	477.0	48.0	513.0	23.0
125Non-alt	548.6	8.5	506.0	20.5	530.5	26.5
25Alt	469.2	77.0	471.5	25.0	515.8	41.0
50Alt	520.5	8.7	470.0	11.0	495.3	4.8
75Alt	500.7	12.5	472.0	5.5	502.5	22.5

[A] After 3rd irrigation event (Wet & Gradient P = 0.01, n/s difference), [B] Prior to 4th irrigation event (Wet P = 0.01, Gradient P = 0.05, n/s difference), [C] After 4th irrigation event (Wet and Gradient P = 0.01, n/s difference).

2003/2004 Season

Investigation of soil moisture recorded on the 31/12/2003 (prior to any irrigations treatments applied) across all plots with NMM tubes installed found the average soil moisture to a depth of 130 cm was 467 mm with a standard deviation of 21 mm (n = 27). Measurements between neighbouring furrows on each side of the plant line prior to the application of any irrigations showed an average difference of 26 mm with a standard deviation of 21 mm (n= 27).

No significant difference in the soil moisture content of neighbouring wet and dry furrows were found for the lowest DI application rate (i.e. 75% commercial practice) across the range of alternations implemented on the 07/01/2004 (i.e. prior to the 3rd irrigation). The average soil moisture gradient across the plant row was 14.9 mm (SE = 4.6), 28.1 mm (SE = 4.6) and 12.9 mm (SE = 14.6) for the 75% Non-alt., Alt every and Alt. 2nd treatments, respectively. Similarly, three days after the 3rd irrigation event there was no significant difference in soil moisture gradient which were 21.5 mm (SE = 4.8), 33.1 mm (SE = 4.7) and 33.5 mm (SE = 14.5) for the 75% Non-alt., Alt every and Alt. 2nd treatments, respectively.

Due to the large variance present within treatments for NMM readings, narrower range of water applied and in season rainfall incursion, no significant differences were founds between DI treatments. Visualisation of soil moisture conditions with the aid of Surfer® demonstrated the soil moisture conditions created (Appendix E). A selected number of Surfer® maps/visualizations demonstrated the gradient present between the wet and dry furrows (LEPA irrigation placement indicated with an arrow, multiple arrows denotes post sprinkler irrigation), non-uniformity in measured soil moisture with the application of irrigation by LEPA socks and the occurrence of preferential flow (by natural cracks or due to shrinkage around the installation tube) (Figure 4.5).

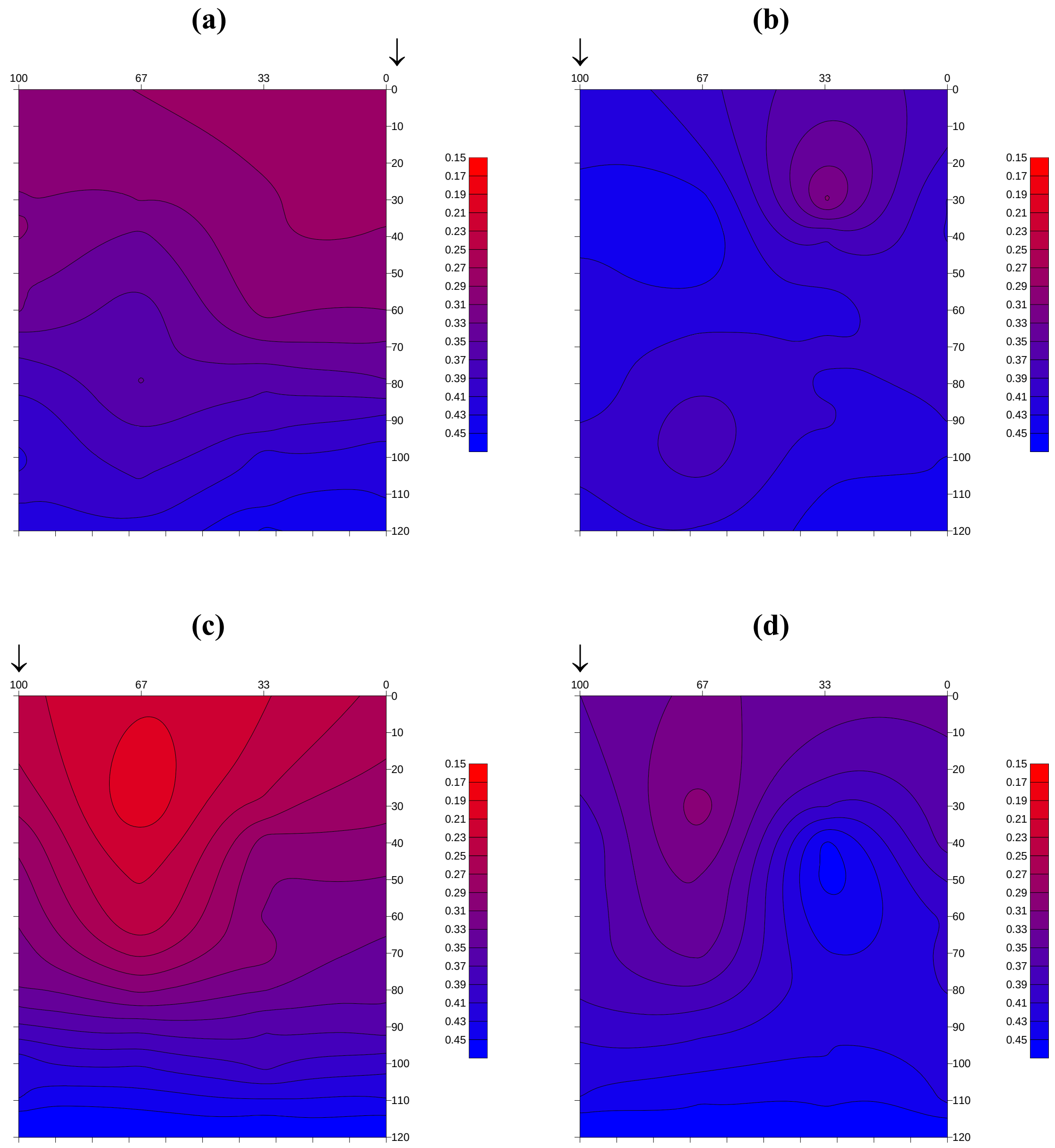


Figure 4.5 Volumetric soil moisture percent, 'Rainbow Valley' (2002/2003) for (a) 75% Alt. every. (Plot 5), - 2 hours before 3rd irrigation, (b) 75% Alt. every. (Plot 5),- 2 hours after 3rd irrigation, (c) 75% Non-alt. (Plot 7), – 2 hours before 3rd irrigation, (d) 75% Non-alt. (Plot 7),– 2 hours after 3rd irrigation

NB: Tubes were located across the plant row at 0, 33, 66 and 99cm, soil depth is present from 0-120cm measured from base of furrow, soil moisture measurements were taken at 30-120cm, 0-30cm is extrapolated.

4.3.2 General Plant Measurements

2002/2003 Season

There was no significant (P<0.05) difference or trend in plant height, total branches or height to node ratio between the DI or PRD treatments at any of the monitoring dates. The only significant difference observed was the number of nodes above white flower (NAWF) between DI treatments on 21/1/03 (Table 4.10).

Table 4.10 Average NAWF for DI treatments 'Macquarie Downs' site on the 21/1/2003 (88DAP)

DI Treatment	Nodes Above White Flower*
25%	4.33 b
50%	3.67 a
75%	3.88 ab
100%	4.28 ab
125%	4.37 b

Figures followed by the same letter are not significantly different from each other (P = 0.05)

2003/2004 Season

No significant difference in the number of fruiting branches was found for any of the DI or PRD treatments at any date except for the 75% DI treatment at 126 DAP (Figure 4.6c). There was also no significant difference in the pre-treatment 4-5 internode length (i.e. at 62 DAP) and no significant difference between PRD and DI treatments for 4-5 inter-node length measured on 22/1/2004 at 85 DAP (Figure 4.7).

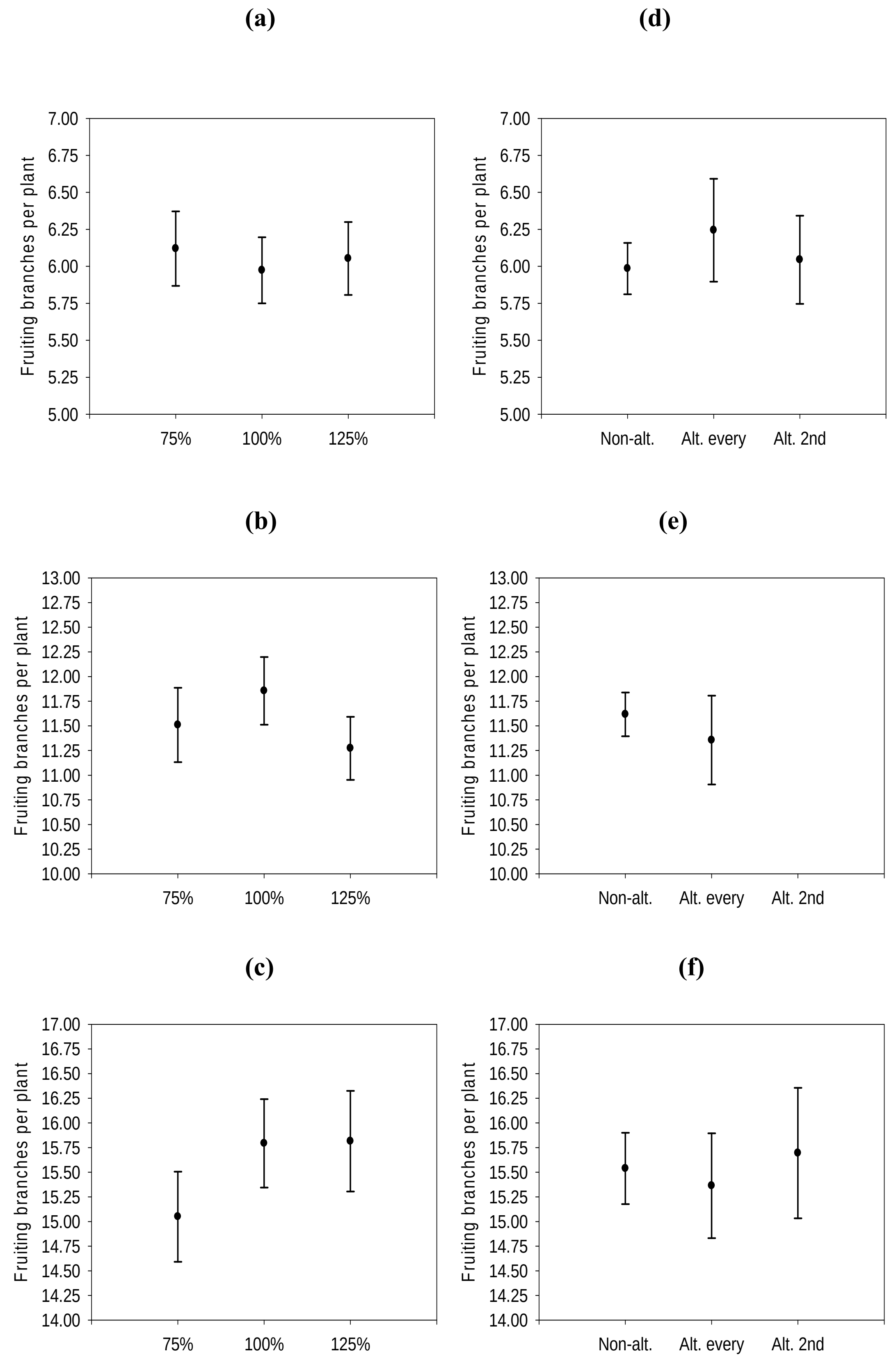


Figure 4.6 Fruiting branches for DI treatments at (a) 62 DAP, (b) 85 DAP and (c) 126 DAP and of PRD treatments at (d) 62 DAP, (e) 85 DAP and (f) 126 DAP, 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval (*P = 0.05*)

(a) (b)

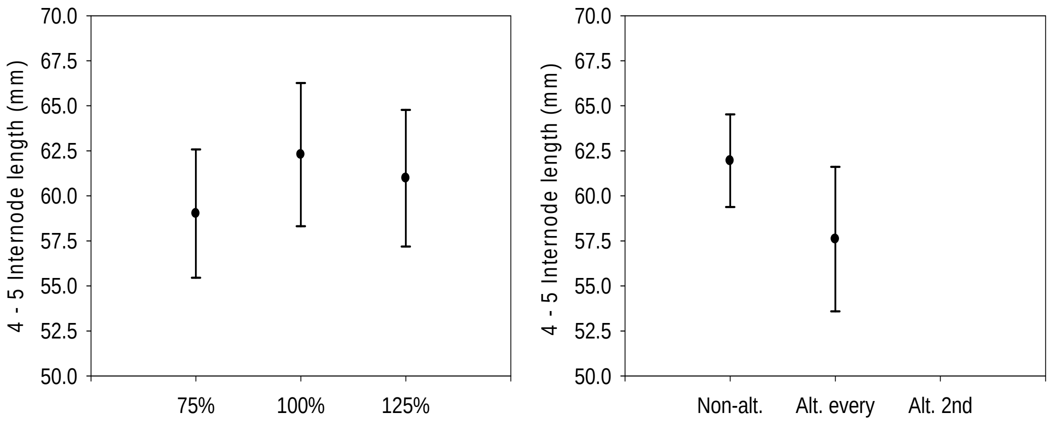


Figure 4.7 Effect of (a) DI and (b) PRD on the 4-5 internode length at 85 DAP, 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval (*P = 0.05*)

4.3.3 Leaf Area

2002/2003 Season

Dry leaf weight was found (Figure 4.8) to be highly correlated (R^2 = 95.9%) with leaf area index (LAI). However, correlations between leaf area and both plant height and shading had an R^2 of 34.0 and 11.7%, respectively. No significant ($P<0.05$) difference in leaf area was found between DI treatments measured on either the 4/2/03 (i.e 102 DAP) or the 27/2/03 (i.e 125 DAP) (data not shown). However, a trend of increasing leaf area with the volume of water applied under the DI treatments was found at 125 DAP.

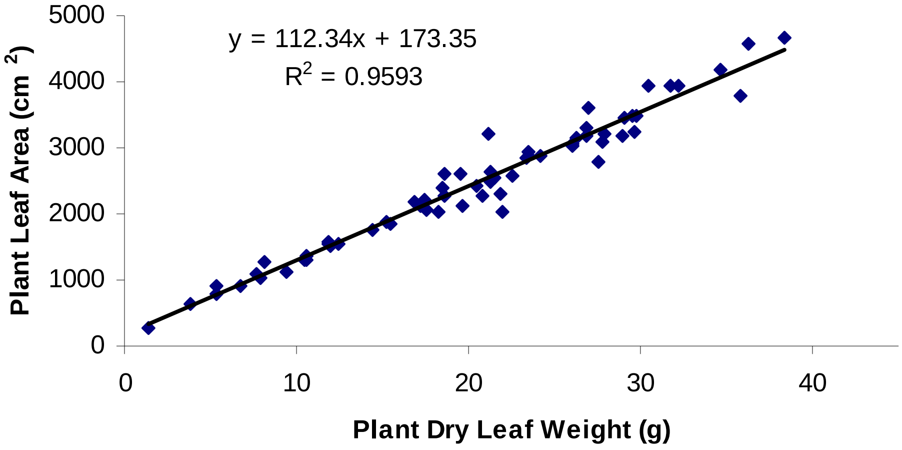


Figure 4.8 Relationship between leaf area and dry leaf weight for cotton (Sicot 80), 'Macquarie Downs' (2002/2003)

2003/2004 Season

Leaf area and dry leaf weight was found (Figure 4.9) to be highly correlated (R^2 = 98.0%). There were no significant differences in leaf area between the DI treatments, PRD treatments or DI by PRD interactions either prior to or after treatment implementation on the 7/1/2004 (70 DAP). However there was a significant difference and trend of increasing LAI with water applied on the 18/2/2004 (112 DAP) (Figure 4.10).

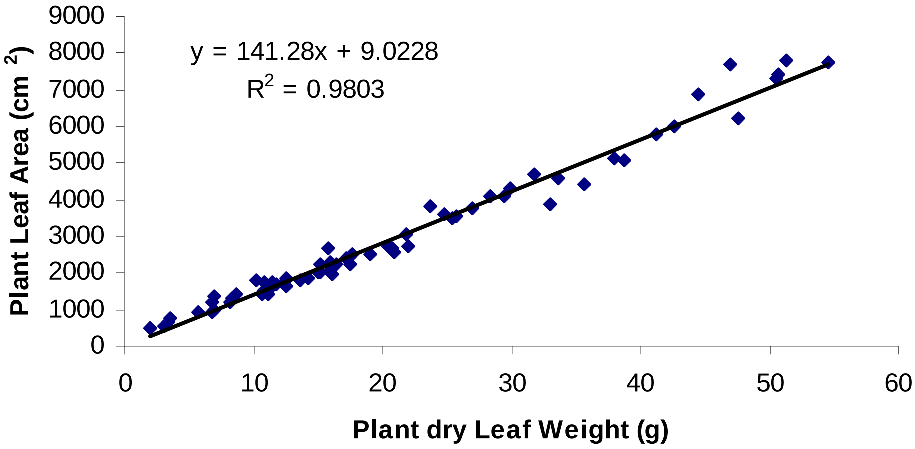


Figure 4.9 Relationship between leaf area and dry leaf weight and leaf area for cotton (Sicot 71), 'Rainbow Valley' (2003/2004)

(a) (b)

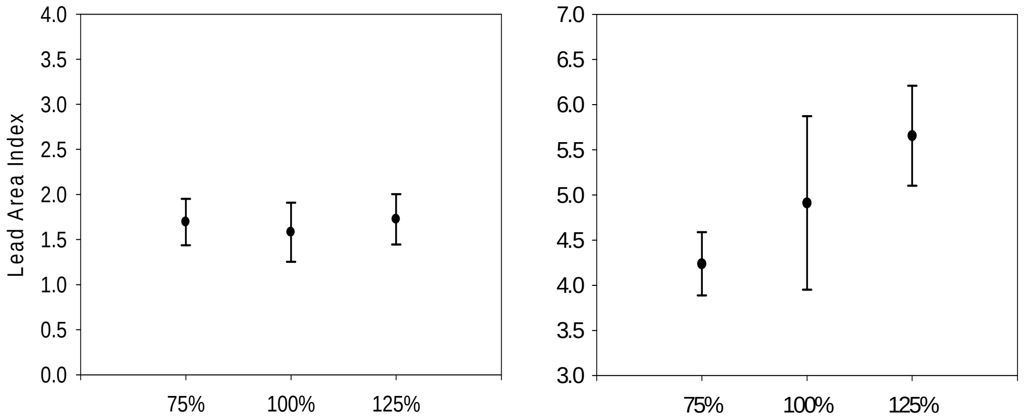


Figure 4.10 Effect of DI on leaf area for cotton (Sicot 71) measured on (a) 07/01/04 (70 DAP) and (b) 18/02/2004 (112 DAP), 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval ($P = 0.05$)

4.3.4 Fruiting Sites and Retention Rate

The number of fruiting sites was square root transformed prior to analysis to conform to the rule of normality (Section 4.2.4). For the 2002-2003 trial, there was no significant difference found in either the number of fruiting sites (Figure 4.11) or fruit retention rates (Figure 4.12) between DI treatments, PRD treatments or DI by PRD interactions. However, the 50% and 75% DI treatments had the highest average final fruiting site number (Figure 4.11) and retention rate (Figure 4.12), respectively. In the 2003-2004 season, there was no significant difference in fruit retention (% fruiting sites retained) or fruiting factor (total fruit [squares & bolls] / fruiting branches) between the DI and PRD treatments at any time during the season (Figures 4.13 and 4.14).

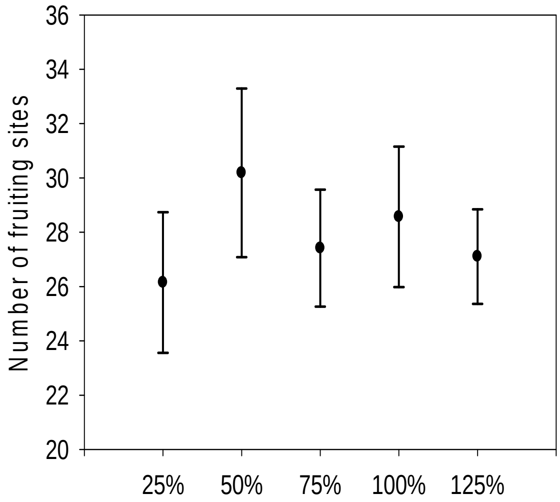


Figure 4.11 Effect of DI on number of fruiting sites (189 DAP) for cotton (Sicot 80), 'Macquarie Downs' (2002/2003)

NB: Error bars represent Confidence Interval (*P = 0.05*)

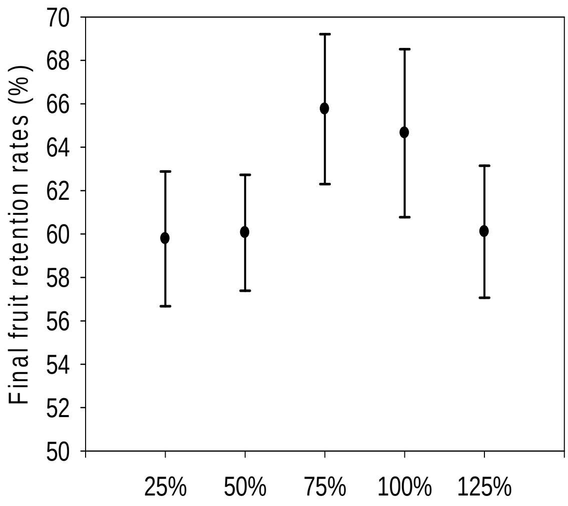


Figure 4.12 Effect of DI on fruit retention rates (189 DAP) for cotton (Sicot 80), 'Macquarie Downs' (2002/2003)

NB: Error bars represent Confidence Interval (*P = 0.05*)

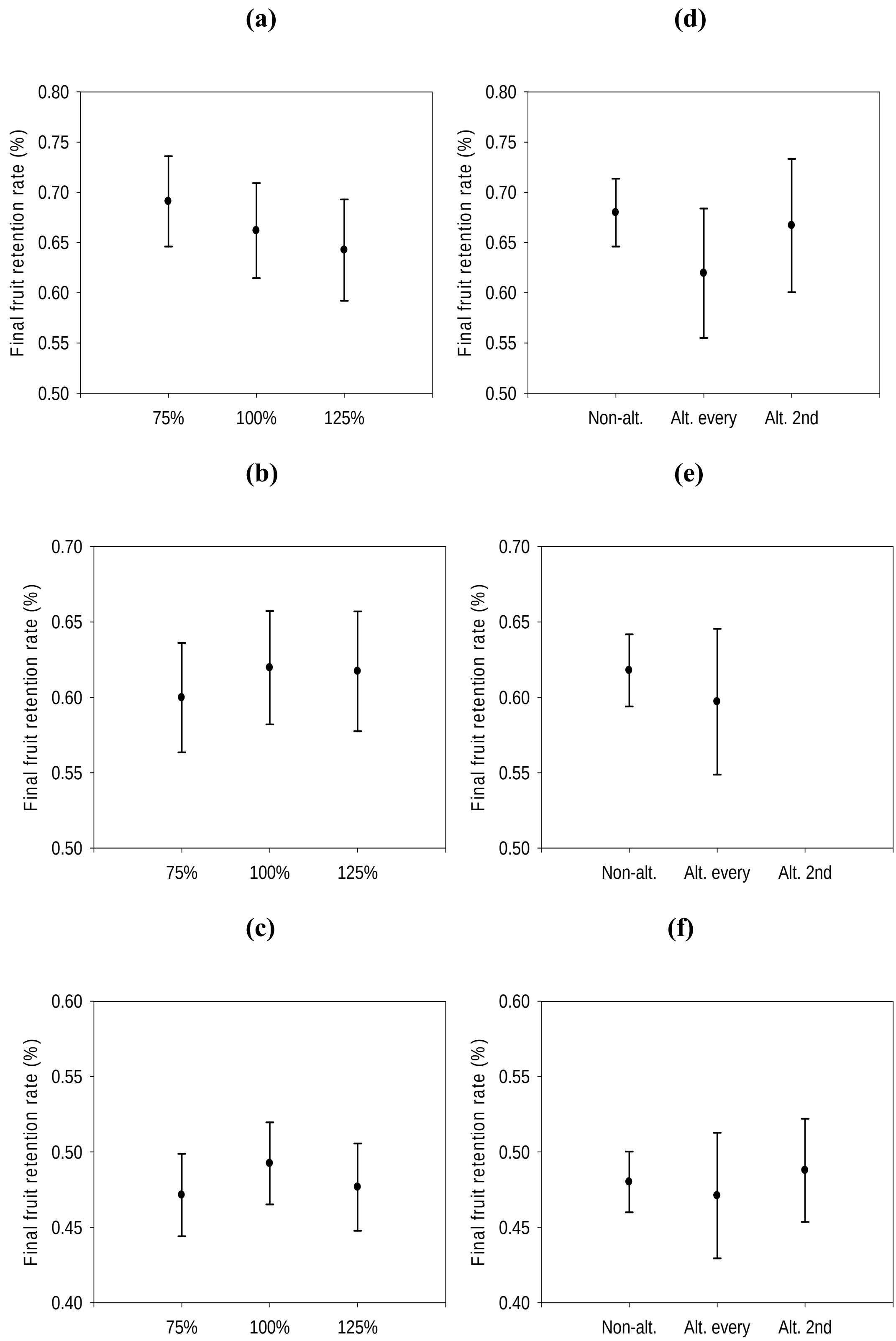


Figure 4.13 Fruit retention for DI treatments at (a) 62 DAP, (b) 85 DAP and (c) 126 DAP and for PRD treatments at (d) 62 DAP, (e) 85 DAP and (f) 126 DAP. Sicot 71, 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval ($P = 0.05$)

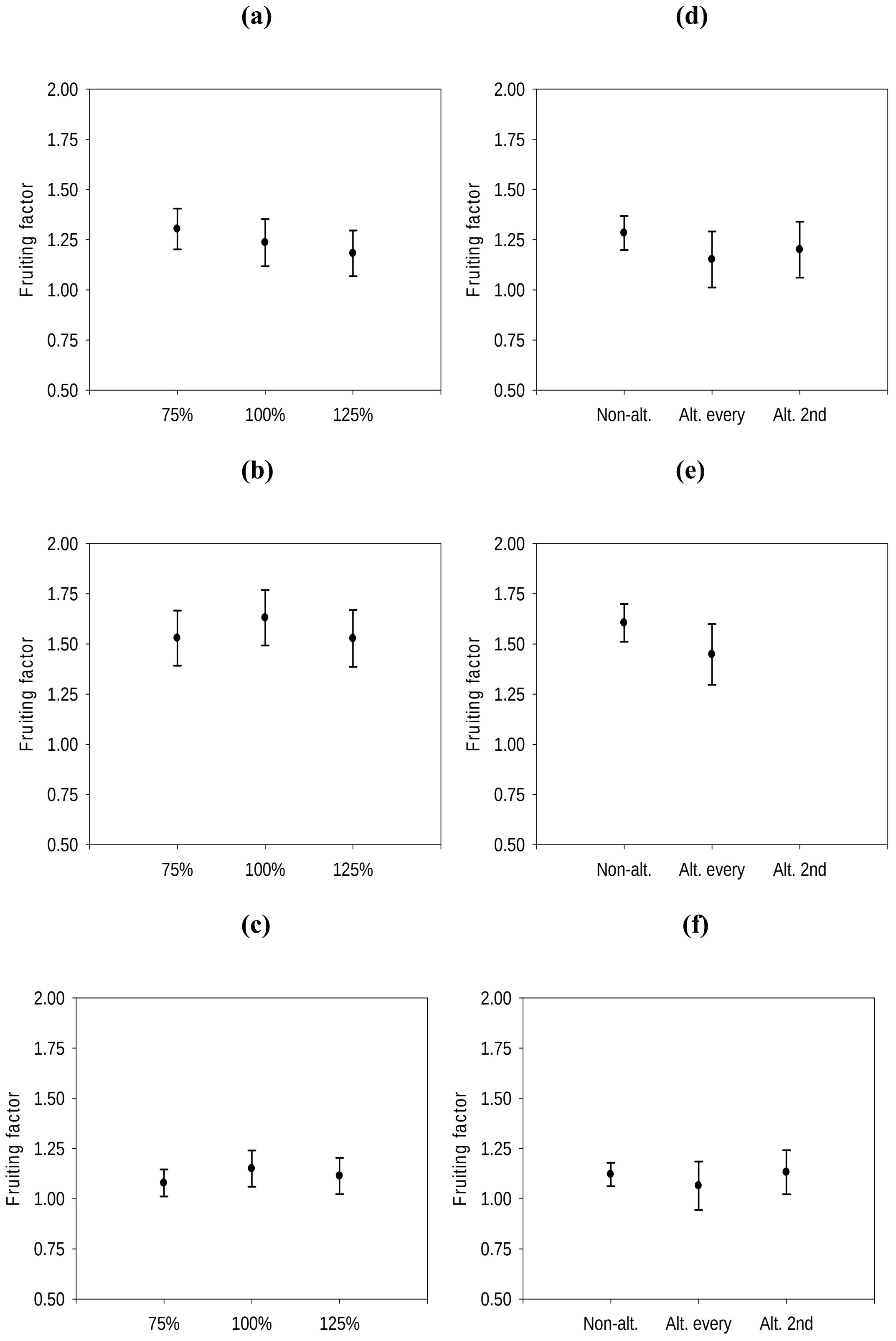


Figure 4.14 Fruit factor for DI treatments at (a) 62 DAP, (b) 109 DAP and (c) 126 DAP and for PRD treatments at (d) 62 DAP, (e) 109 DAP and (f) 126 DAP. Sicot 71, 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval (*P = 0.05*)

4.3.5 Harvest Data

2002/2003 Season

A significant difference ($P<0.05$) in total harvested weight was found between the 25% DI treatment and all other DI treatments (Figure 4.15). However, there were no significant differences between any of these other DI treatments. There was also no significant difference in total harvested cotton lint between the alternated (PRD) and non-alternated (i.e. DI) treatments or any interaction between the PRD and DI treatments.

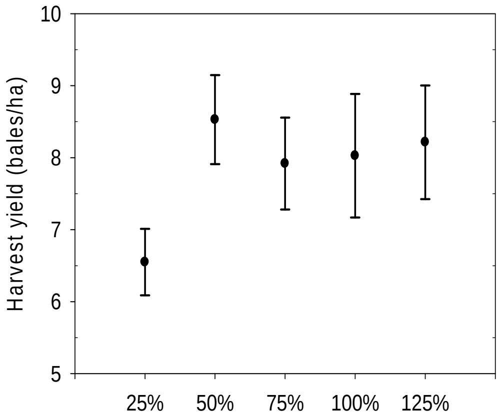


Figure 4.15 Cotton yield (bales/ha) for the DI treatments, 'Macquarie Downs' (2002/2003)

NB: Error bars represent Confidence Interval ($P = 0.05$)

Grouping of the DI treatment weights by harvest date showed that an increasing moisture stress increased the proportion of total cotton lint yield harvested (maturing) earlier in the season (Figure 4.16). The crop GPWUI (bales/ML_{Total}) of the treatments ranged from 1.11 to 1.46 bales/ML_{total} with a maximum at 79% Et replaced (Table 4.11). The $IWUI_{Applied}$ ranged from 2.28 to 4.35 bales/$ML_{Applied}$ with the maximum achieved when 79 % ET was applied.

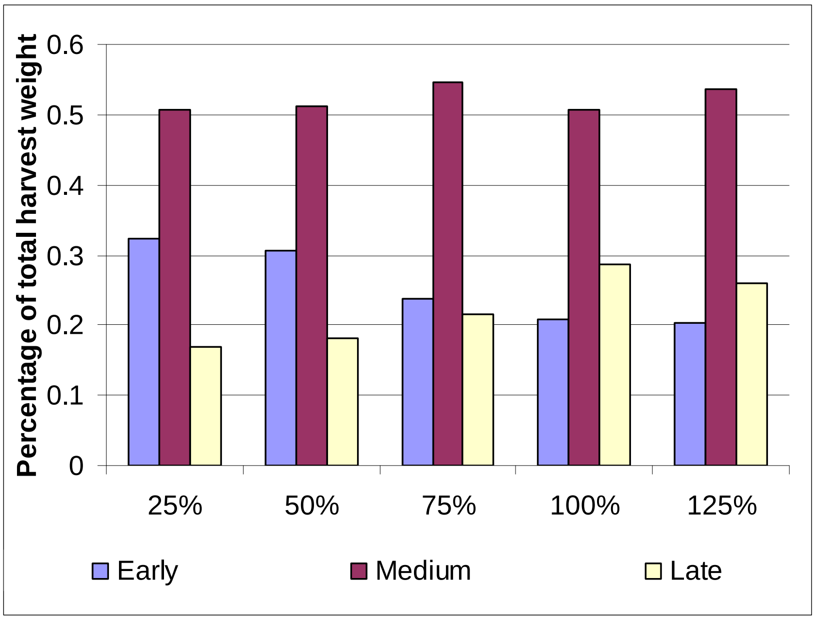


Figure 4.16 Effect of DI treatments on the earliness of yield, 'Macquarie Downs' (2002/2003)

Categories are Early = up to 146 DAP, Medium = 147-165DAP and Late = 166-188DAP maturing

Table 4.11 Performance indices of DI treatments, 'Macquarie Downs' (2002/2003)

DI Treatment	Potential ET replaced (%)	GPWUI (bales/ML_{total}) [A]	$IWUI_{Applied}$ ($Bales/ML_{Applied}$)[B]
25%	71 %	1.25 b	4.35 a
50%	79 %	1.46 a	4.20 a
75%	86 %	1.24 b	3.10 b
100%	93 %	1.17 b	2.61 ca
125%	100 %	1.11 b	2.28 ca

[A] Gross production water use index (GPWUI) is calculated on estimated yield/ha from assumed 40% gin turnout divided by total water available to the crop (combining stored soil moisture, rainfall and irrigation water applied).

[B] Irrigation water use index applied ($IWUI_{Applied}$) is calculated on estimated yield/ha from assumed 40% gin turnout divided by total water applied to the crop as irrigation water only.

Figures followed by the same letter are not significantly different from each other within columns (P = 0.05)

A significant difference in harvested boll number was found between the 25% and 50% DI treatment with no significant difference between the other DI treatments (Figure 4.17). Boll weight was found to increase with irrigation water applied (Figure 4.17). However, the only significant difference in average boll weight was found between the 25% and 125% DI treatments.

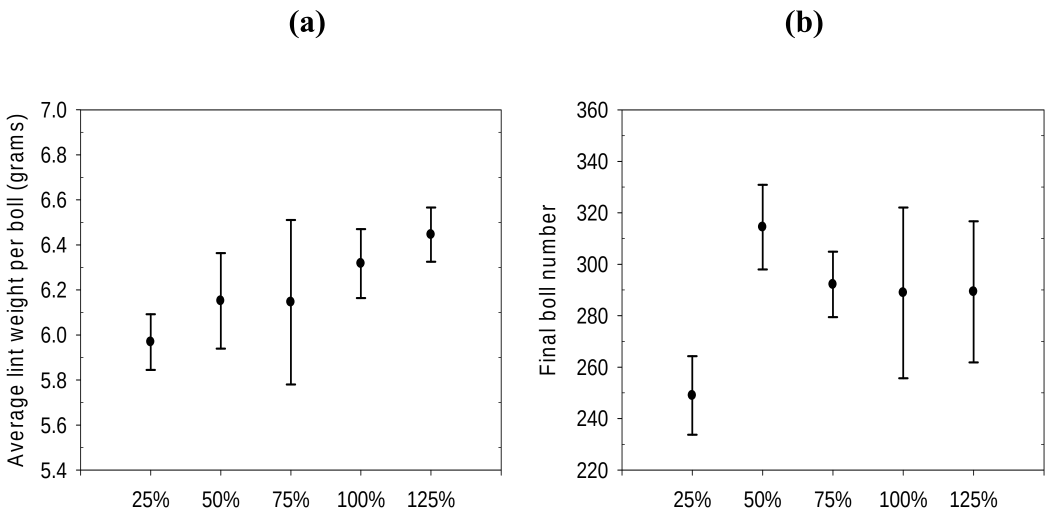


Figure 4.17 Effect of DI on (a) lint weight per boll and (b) boll number (2 x 2m of plant row), 'Macquarie Downs' (2002/2003)

NB: Error bars represent Confidence Interval (*P = 0.05*)

2003/2004 Season

The GPWUI in the 2003/2004 season ranged from 1.18 to 1.24 bales/ML_{total} with the $IWUI_{Applied}$ ranging from 3.23 to 3.95 bales/$ML_{Applied}$ (Table 4.12).

Table 4.12 Performance indices of DI treatments, 'Rainbow Valley' (2003/2004)

DI Treatment	Potential ET % replaced	GPWUI (bales/ML_{total})[A]	$IWUI_{Applied}$ (Bales/$Ml_{Applied}$)[B]
75% (30mm per pass)	77.5 %	1.23 a	3.95 a
100% (40mm per pass)	80.8 %	1.24 a	3.66 a
125% (50mm per pass)	84.1 %	1.18 a	3.23 b

[A] Gross production water use index (GPWUI)is calculated on estimated yield/ha from assumed 40% gin turnout divided by total water available to the crop (combining stored soil moisture, rainfall and irrigation water applied).

[B] Irrigation water use index applied ($IWUI_{Applied}$) is calculated on estimated yield/ha from assumed 40% gin turnout divided by total water applied to the crop as irrigation water only.

Figures followed by the same letter are not significantly different from each other within columns (P = 0.05)

There was no significant difference in total harvested cotton lint between alternated (PRD) and non-alternated (DI) treatments or any interaction between PRD and DI treatments (Figure 4.18). Reducing the volume of water applied produce a slight increase in the earliness of crop maturity (Figure 4.19). There were no significant differences in either the harvest boll number and average weight of bolls (Figure 4.20 & 4.21) between the PRD or DI treatments.

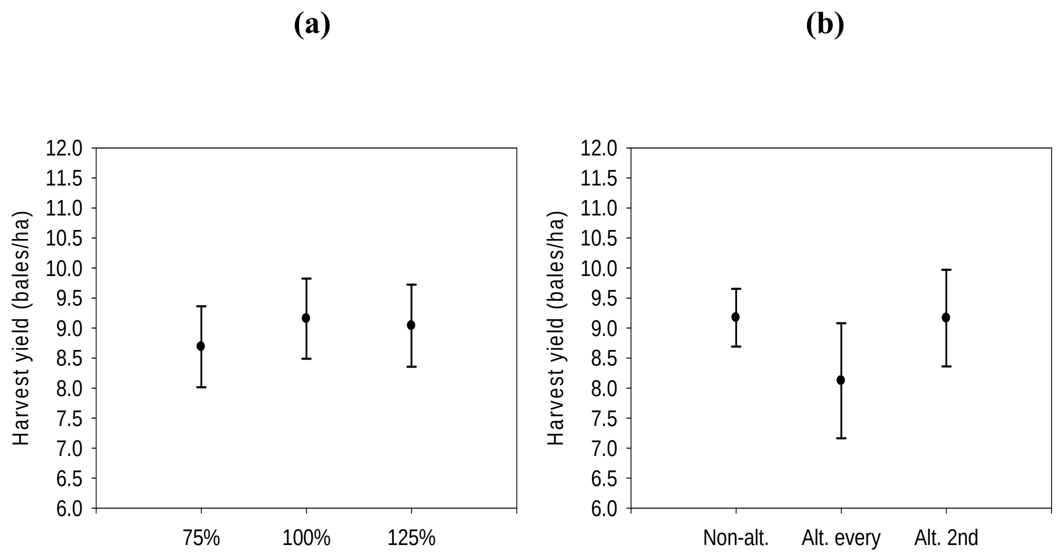


Figure 4.18 Effect of (a) DI and (b) PRD on cotton yield (bales/ha), 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval (*P = 0.05*)

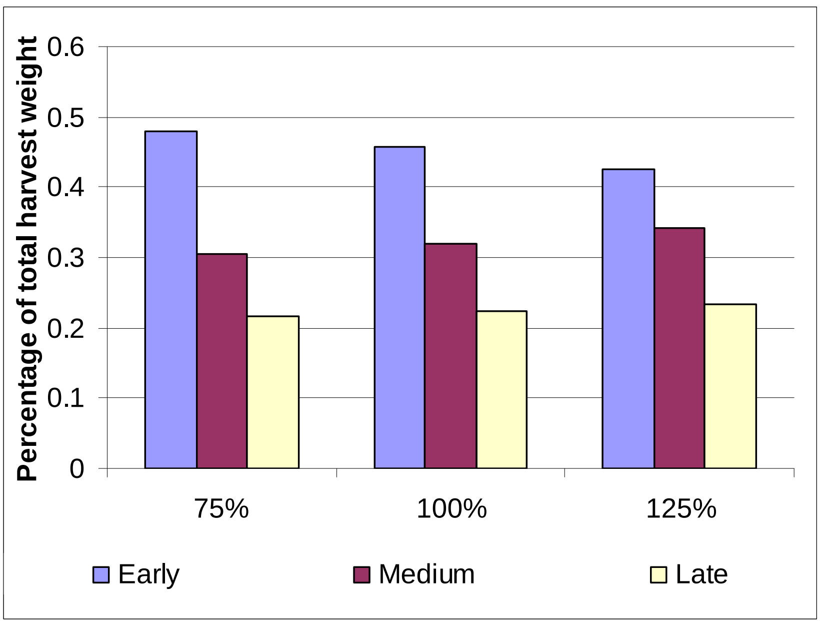


Figure 4.19 Effect of DI treatments on the earliness of yield, 'Rainbow Valley' (2003/2004)

Categories are Early = up to 159 DAP, Medium = 160-169 DAP and Late = 170-181 DAP maturing

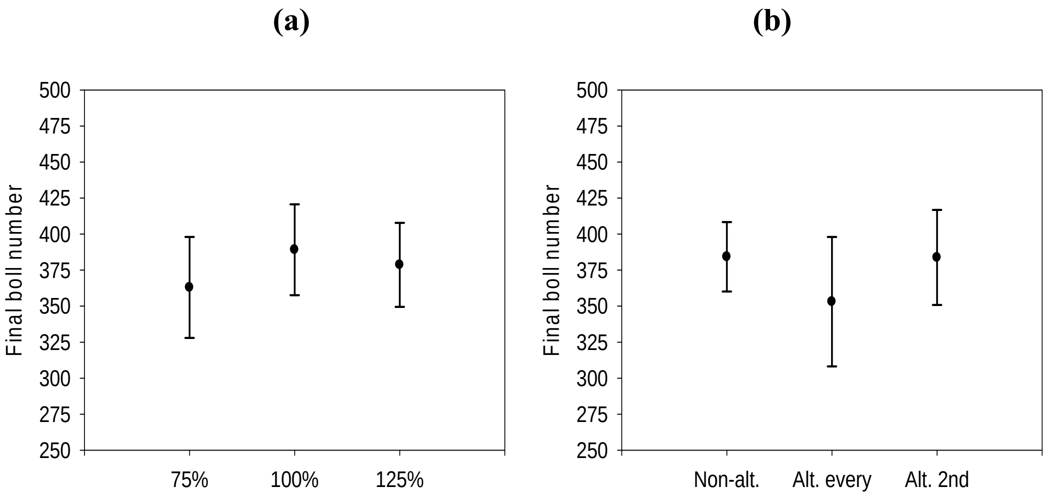


Figure 4.20 Average harvested boll number (2 x 2m of plant row) for (a) DI and (b) PRD treatments, 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval (*P = 0.05*)

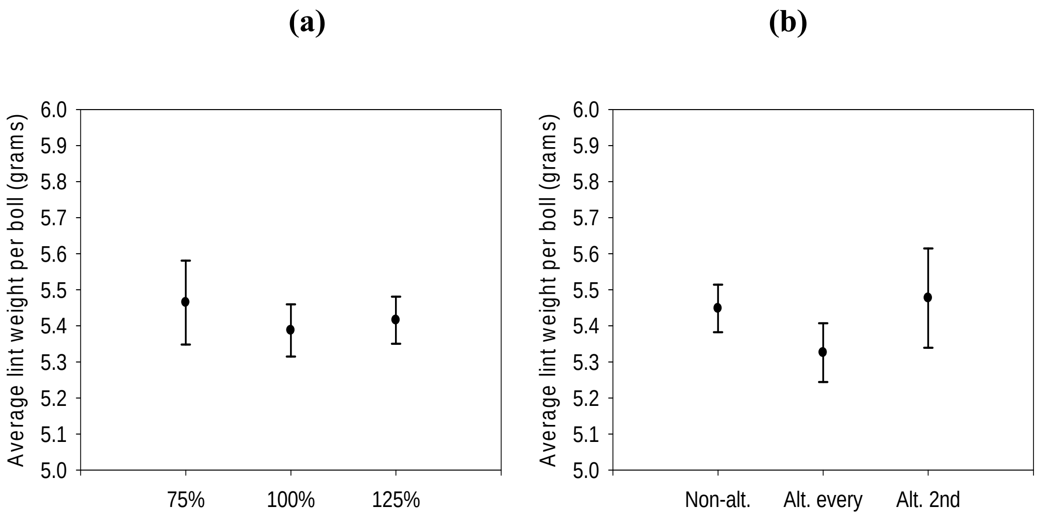


Figure 4.21 Average harvested boll weight (2 x 2m of plant row) for (a) DI and (b) PRD treatments, 'Rainbow Valley' (2003/2004)

NB: Error bars represent Confidence Interval (*P = 0.05*)

4.4 Discussion

4.4.1 Soil Moisture

Soil moisture conditions prior to the implementation of variable irrigation volumes with the use of LEPA socks, were found to have only a small degree of variation between plots in both years. However, a much greater degree of variability in soil moisture conditions was found for both years when comparing soil moisture measured with a single tube in neighbouring furrows. This demonstrates the localized differences in soil moisture which can exist and the degree of variance in readings which can occur when relying on only a point source soil moisture measure.

Measuring four NMM tubes in each plot (Figure 4.4) did not improve the ability to identify significant differences in soil moisture between the deficit treatments applied. No significant differences in soil moisture between DI treatments were found prior to the second and fourth irrigation event (Table 4.7). However, a limited trend did occur in soil moisture measured after the 3rd irrigation event. Hence, it seems likely that there was an increase in plant extraction with increased availability of soil moisture present. Alternatively, it may demonstrate that differences in root zone soil moisture can only be effectively measured directly after irrigation is applied. This may be due to the variability of the point source soil moisture measurements on cracking clay soils and/or the influence of rainfall during the season (Figure 4.2). Increases in the number of replications imposed may also have limited or reduced the degree of variability which occurred.

Visual representations of the root zone soil moisture content show uneven wetting patterns on the irrigated side (Figure 4.5a) and preferential flow down beside some of the access tubes (Figure 4.5b). The variability in wetting patterns measured was found to be greater with smaller irrigation applications and may be attributed to the increase in cracks and preferential flow paths in the presence of larger deficits.

Due to the presence of preferential flow paths, a high degree of soil moisture variability was observed when comparing neighbouring furrows for the DI (Table 4.8) and full range of irrigation treatments (Table 4.9). This highlights the inherent soil moisture variability across fields and the limitations of point source measurements for monitoring field soil moisture status (especially under irrigations applied by LEPA sock). The problem of preferential flow beside access tubes may have been further exacerbated by the placement of the tubes in the furrow which is subject to a greater occurrence of cracking.

There were no significant differences in the soil moisture gradient either before or after irrigation events applied by LEPA sock (Table 4.9). This suggests an inability to retain the applied water on the nominal wet side of the plant row due to preferential flow paths even when smaller (e.g. 25% of commercial practice) volumes are applied. The occurrence of in crop rainfall may have also caused disruption to the soil moisture trend with irrigation volumes applied and reduced the ability to create a significant soil moisture gradient between neighbouring furrows.

There was no significant difference in the size of the soil moisture gradient between neighbouring furrows for either the alternated or non-alternated treatments across the range of deficits applied. However, to evaluate whether PRD conditions were present, the size of gradient produced should be assessed in terms of the moisture potential equivalent and the amount of soil moisture content on the wet side. If the wet side is kept wet (i.e. <33kPa) and a sizeable suitable gradient (i.e.>200kPa) is created across the plant root zone this would be considered as PRD (i.e. biochemical signalling). However, if the wet side is not kept wet (i.e. >33kPa) and the same level of gradient is present (i.e. >200kPa), crop response is more likely to be due to deficit irrigation (i.e. hydraulic and biochemical signalling). The size of potential root zone gradient suggested as necessary (Chapter 3) to create a PRD signalling event is equivalent to a moisture content gradient across the neighbouring furrows of more than 450mm (in a metre of soil). This level of moisture gradient was not achieved in either field season with the largest gradient measured in 2002/2003 being 77 mm after the 3rd irrigation event was applied. Hence, it would seem unlikely that PRD root zone conditions can be applied in the field on cracking clay soil using LEPA socks.

4.4.2 Leaf Area Correlations

Leaf weight was found to be highly correlated (R^2 values > 96%) with leaf area in both field seasons (Figure 4.8 & 4.9). However, poor correlations (R^2 values < 35%) were found between leaf area and both plant height and shading in the 2002-2003 season. Similarly, a comparison of measured plant height with leaf area index calculated using an equation used by other workers (Richards *et al.* 2002) also produced a poor (R^2 = 34%) correlation. This suggests that tipping out and the presence of non-uniformity in plant stand had an affect on plant height, shading and leaf area.

The trend towards increasing leaf area and dry matter accumulation with increasing soil moisture availability (Figure 4.10) has been found in cotton by others (Gerik, Landivar & Faver 1994, Hearn 1994, Turner *et al.* 1986, Yazar, Sezen & Sesveren 2002). However, there was no significant difference in leaf area and dry weight measurements between the DI and PRD treatments, probably due to the late implementation of the treatments. At this relatively late stage of development, vegetative growth is limited in favour of boll development (as fruit loads are developed) and the effect of moisture stress on leaf area is reduced.

4.4.3 Deficit Irrigation

This work has demonstrated that the application of a soil moisture deficit late in the season produces water use productivity and crop maturity benefits. The 2002-03 harvest results (Table 4.11) confirmed the benefits of imposing late season soil moisture deficits with GPWUI increasing from 1.11 bales/ML_{total} for the 125% DI (100%ET) treatment to 1.46 bales/MLtotal in the 50% DI (79% ET) treatment. The yield in the 50% and 125% DI treatments were similar with the 50% DI treatment receiving 1.58 ML/ha less irrigation water. The yield was maintained with reduced water application due to an increased number of harvested bolls associated with an increase in fruiting sites and retention rate (Figure 4.11 & 4.12). Deficit irrigation was also found to increase crop earliness in both seasons (Figure 4.16 & Figure 4.19) confirming that increasing the soil moisture deficit increases the rate of boll development and crop maturity.

In general, the lack of significant differences between DI treatments for in-season plant measurements, leaf area, final fruiting sites and final fruit retention was most likely due to the late implementation of the DI treatments in 2002-2003, and the high level of in-season rainfall in both years. The only significant difference between deficit irrigation treatments in 2002-2003 was for NAWF measured at 88 DAP (Table 4.10). This difference in NAWF is directly related to the rate of growth under the prevailing soil moisture conditions. At this date, both extremes of DI treatment were found to have a larger number of NAWF. The 25% DI treatment produced more NAWF due to excessive fruit shedding from limited water availability causing water stress and reducing the plant's capacity to carry bolls. This in turn eliminated some of the assimilate demand and once the stress was relieved there was a compensatory increase in the vegetative growth rate. The higher NAWF in the 125% DI treatment occurred due to an increase in vegetative growth rate associated with higher fruit shedding because of the higher soil moisture availability.

The only significant difference between deficit irrigation treatments during 2003-2004 was for leaf area at 112 DAP (Figure 4.10) and for average fruiting branches at 126 DAP (Figure 4.6). The trend generally reflected a reduction in vegetative growth (i.e. leaf area and branches) with a reduction in water applied. This trend of reducing vegetative growth and increasing boll retention with a reduction in water application is consistent with other research (e.g. Yazar, Sezen & Sesveren 2002). However, due to the considerable in-season rain during the 2003-2004 trial, the differences in leaf area between treatments was not carried through to the end of the season.

For both seasons of field trials, the optimum GPWUI occurred when approximately 75-80% of seasonal ET was replaced (Table 4.3 & Table 4.6). This is similar to previous deficit irrigation results reported for cotton overseas (Bordovsky *et al.* 1992, Hutmacher *et al.* 1994, Yazar, Sezen & Sesveren 2002). However, it should be noted that gross ET replacement is a poor indicator of yield and crop performance without some quantification of the specific soil moisture deficit or plant water status required at each stage of crop development. Hence, there is a requirement for further research to better define the target stress and/or range of soil moisture deficits required to optimize crop water use productivity for each physiological stage of development. It also seems likely that the potential to effectively apply and obtain a benefit from deficit irrigation strategies will be a function of the in-season rainfall and seasonal climatic variability.

The ability to accurately forecast rainfall (inter and intra-season) and minimise waterlogging and water stress by more frequent irrigations using smaller volumes (which do not fill the soil moisture profile), should also promote further opportunities to improve water use productivity, increase yield potential and reduce deep drainage. Similarly, the effective implementation of water limiting irrigation strategies in commercial crops will require real-time monitoring of soil or plant water status, an understanding of the plant response to the deficit irrigation strategy and a prediction of future weather conditions.

4.4.4 Partial Rootzone Drying

The PRD strategies applied in both field trials failed to produce any significant difference in plant height, height to node ratio, fruiting sites, percent retention or harvest weights. However, several environmental and irrigation management factors may have influenced the potential to effectively apply appropriate root zone moisture conditions for PRD. For example, the redistribution of irrigation water via macro-flow observed for the cracking clay soil and the amount of in-season rainfall both contributed to substantial periods when there were similar water contents on both sides of the plant row. As successful PRD implementation requires the maintenance of both wet and dry areas of the root ones to produce hormonal signalling (Davies, Wilkinson & Loveys 2002, Dry & Loveys 1999, Dry & Loveys 1998, Stoll, Loveys & Dry 2000) it is possible that the soil moisture gradients applied in the field trials were insufficient for signalling to occur. Similarly, the PRD treatments were applied relatively late in the season and there were a relatively small number of PRD alternations which may also have reduced the potential hormonal signalling and physiological response.

These field trials highlight practical limitations of applying PRD strategies particularly where cracking clay soils are used in areas which are likely to experience substantial in-season rainfall. The successful implementation of PRD under field conditions is likely to require low levels of in-season rainfall, small irrigation deficits and application volumes to reduce the potential for redistribution via macro-flow across the plant row and/or will need to be conducted on a non-cracking soil with low lateral soil moisture movement (e.g. sands). This suggests that if PRD is to be implemented in the cotton industry then it is most likely to be successful in areas of light soil which receive limited in-season rainfall. However, further research is required to better refine the likely area of potential implementation in the Australian cotton industry and the probable benefits from PRD implementation in these areas.

There are a host of interacting factors which affect the ability of cotton to produce and retain fruit, and achieve a given level of yield and water use productivity. These include: crop variety, plant density, nutrition, soil moisture variation, insect pressure, growth control and climatic conditions (e.g radiation, temperature, wind and rainfall). It is unlikely therefore that one fixed irrigation strategy will be found to achieve the desired plant architecture, vegetative growth rate, carrying capacity, earliness, water use productivity improvement and yield for all seasonal conditions (i.e. there is no silver bullet). It may be more practical to consider a dynamic irrigation schedule which changes as a result of biotic and abiotic conditions. Hence, further field trials involving the monitoring of soil moisture and plant responses under a range of climatic and irrigation management conditions are required to confirm the potential for obtaining production benefits from PRD. However, a preliminary step prior to conducting further field evaluations should be to assess the probability of in-season rainfall for a given geographical area and the prediction of soil moisture gradients achievable under various irrigation strategies on soils commonly used to grow cotton.

4.5 Conclusion

Field trials to evaluate DI and PRD strategies were conducted on commercial cotton farms over two seasons. Significant differences in GPWUI were found between DI treatments suggesting that the application of mild soil moisture deficits (75-80% ET) late in the season can reduce irrigation water requirements while maintaining yields. Improvements in crop water use productivity for deficit irrigation crops resulted from an increase in fruit retention rates and the number of bolls harvested. No significant yield or water use productivity benefits were found due to the application of PRD strategies in these field trials. However, the PRD results are likely to have been affected by the high in-season rainfall, concerns over the ability to consistently create adequate soil moisture gradients across the plant line, and the limited potential to apply the full range of PRD alternation strategies possible.

A number of barriers to the successful implementation of DI and PRD in the Australian cotton industry were identified. For example, the soil moisture deficits at which the irrigations are commonly applied to cracking clay soils often result in large crack volumes which limit the potential to retain applied water on one side of the plant row. Similarly, the presence of in-season rainfall also limits the ability to impose deficit irrigation and maintain soil moisture gradients across the plant line. Hence, it seems likely that the potential to obtain a benefit from either DI or PRD strategies in the cotton industry will be dependent on a range of environmental (e.g. climatic, soil), irrigation management (e.g. target deficit) and plant related factors (e.g. crop stage).

5.0 CLIMATIC AND SOIL FACTORS INFLUENCING IMPLIMENTATION OF PRD WITHIN THE AUSTRALIAN COTTON INDUSTRY

The application of deficit irrigation (DI) in cotton using large mobile irrigation machines (LMIMs) has shown (Chapter 4) that significant improvement in the irrigation water use index $_{\text{(Applied)}}$ ($IWUI_{Applied}$) and gross production water use index (GPWUI) can be achieved compared to current commercial irrigation scheduling practices. While the application of partial rootzone drying (PRD) was found to produce an AbA response in split-pots under glasshouse conditions (Chapter 3), no significant crop response to PRD was found in the field trials (Chapter 4). However, the inability to identify a crop response in the PRD field trials may have been due to difficulties associated with creating the appropriate root zone soil moisture deficits and gradient. Factors which influence the development of the required root zone moisture conditions include the presence of in-season rainfall and the potential for soil-water movement within the root zone .

This chapter evaluates the impact of rainfall frequency and soil-water movement on the potential to apply PRD under field conditions experienced in the cotton industry. Section 5.1 uses historic in-crop rainfall data and assumed management requirements for PRD to identify the probability of getting appropriate windows of opportunity to apply PRD strategies in each of the Australian cotton growing regions. Section 5.2 uses field data and a calibrated soil-water model to evaluate the impact of various irrigation application strategies and soil hydraulic properties on the potential to create the soil moisture conditions required to trigger a PRD crop response.

5.1 Regional Climatic Limitations to the Application of PRD in the Australian Cotton Industry

5.1.1 Introduction

There is currently widespread industry interest in the application of alternative irrigation strategies (e.g PRD and DI) for cotton grown under centre pivots and lateral move machines. However, the success of irrigation management strategies that rely on maintaining the soil moisture within a defined range are heavily influenced by the soil and climatic conditions experienced. Both PRD and RDI rely on the development and maintenance of specific soil moisture deficits. Hence, the period over which they can be successfully applied is a function of both the time required for the appropriate soil moisture deficit condition to be imposed (e.g. the period required to draw down the soil moisture to the required deficit level will be a function of the soils water holding capacity and crop water use) and the period over which the desired condition can be maintained before disruption (e.g. interference due to in-crop rainfall).

It is difficult to successfully implement PRD strategies in row crops when there is significant and regular in-crop rainfall as the rainfall reduces the soil-moisture gradient across the plant row. Probabilistic assessments of in-crop rainfall events based on both historic data and climatic prediction indices provide a basis for evaluating in-season rainfall “risk” for different regions. Use of climatic predictors (e.g. southern oscillation index (SOI) and sea surface temp (SST)) can also provide a seasonal refinement to forecasting the probability of in-crop rainfall disruption. Hence, the objective of this study was to evaluate the risk of in-season rainfall using a climatic predictor and to determine the probability of being able to successfully implement a PRD irrigation strategy for cotton in each of the main Australian cotton growing regions.

5.1.2 Methodology

Bureau of Meteorology (BOM) weather data for the period 1900 – 2004 was collated for each of the main cotton growing regions in Queensland and New South Wales. The raw BOM data was pre-processed into an appropriate format and input into a customised program to calculate the number of PRD signalling days not interrupted by rainfall for each region and year. Other input data required included the (a) window of opportunity (i.e. starting and finishing dates) for applying PRD strategies within the season, (b) threshold volume of rainfall in a single event (daily) required to trigger disruption to the PRD root zone conditions, and (c) period required for the crop to deplete the soil-water to the deficit level necessary to initiate PRD signalling.

The starting date chosen for the analyses was the 1st December and the finishing date was the 31st January as this period encompasses the initiation of flowering and early fruit development. The volume of rainfall in a single event required to disrupt the PRD soil-moisture conditions was assumed to be 10 mm. The readily available water (RAW) content for re-irrigation used in the cotton industry is assumed to be 50% of the plant available water content (PAWC) (Milroy, Goyne & Larsen 2002). Two contrasting soil types were chosen for the analysis. The plant available water capacity was assumed to be 120 mm for the sand-loam and 200 mm for the heavy clay. There values were used to calculate the re-irrigation deficit for the wet side of the root zone. However, a larger than normal level of soil moisture deficit is required on the dry side of the root zone to initiate an elevation of AbA within the crop (Chapter 3). Hence, it was assumed that the period required to initiate PRD signalling was twice the period required to reach re-irrigation deficit on the wet side of the plant. It was also assumed that, a further seven days of stress would be required to obtain any appreciable growth or yield difference due to the PRD conditions. The soil-water extraction rate (i.e. evaporation) for cotton during the period was assumed to be 12 mm/day. Hence, the interval calculated between re-irrigations on the 'wet side' of the root zone ranged from 5 days for the sandy loam to 8.3 days for the heavy clay (Table 5.1).

Table 5.1 Effect of soil texture on the period between irrigations and the period to initiate PRD signalling

Soil texture	PAWC (mm)	RAW (mm)	PRD wet Re-irrigation	Dry-down time for PRD signalling[A]
Sandy-loam	120	60	5 days	17
Heavy clay	200	100	8.3 days	24

[A] 2 x re-irrigation period + 7 signalling days

PAWC = Plant available water capacity, RAW = Readily available water, PRD = Partial Rootzone Drying

FlowCast® Version 3.4.1.1 (QNRM&W/MDBC, 2003) was used to calculate the probability distribution for the number of signalling days in each season for each of the cotton regions. FlowCast® is a time-series analysis tool used for exploring and forecasting time-series data. It was originally developed as a post-processor for hydrological models but is a generic tool capable of analysing any time-series data.

The use of Flowcast® also enabled separate identification of the signalling days in each region based on the southern oscillation index (SOI) as measured three months prior to the period of interest with no lead time. This enabled forecasting based on the likelihood of successfully achieving a PRD signalling event for a region on the basis of the 3 month SOI outlook for each region. No testing of the skill level of using SOI for the range of regions investigated was undertaken during this study.

5.1.3 Results

5.1.3.1 Effect of rainfall and soil-water holding capacity on successful implementation of PRD

There was a substantial variation in the potential to successfully implement PRD depending on the region and soil (Table 5.2). For seven days of PRD signalling on sandy loam soils, PRD could be implemented successfully in most years (i.e. at least 9 out of every 10 years) where cotton is grown in the St George, Dirranbandi, Warren, Hillston and Bourke regions. The probability decreased to between 7 and 9 years out of every 10 for other cotton growing regions. For heavy clay soils, the probability of successfully implementing PRD was between 2 and 6 years out of every 10 years for the Biloela, Dalby and Emerald areas and between 6 and 9 years out of every 10 for the remaining regions. Probability in all regions decreased when assessed for likelihood of achieving two weeks of signalling (Table 5.3) instead of one week.

Table 5.2 Probability of obtaining seven days of PRD signalling, for each cotton region for the period of interest (1st December- 31st January)

Soil	Sandy loam (17 days)				Heavy clay (24 days)			
Region	All years	El Nino SOI <=-5	Medium -5< SOI <5	La Nina SOI>=5	All years	El Nino SOI <=-5	Medium -5< SOI <5	La Nina SOI>=5
Biloela	90.0	97.5	85.5	88.2	64.7	81.4	62.9	48.8
Dalby	88.1	92.2	91.1	79.2	67.1	74.3	76.9	44.7
Emerald	92.2	97.7	92.7	85.5	74.9	81.6	78.8	61.8
Narrabri	95.8	99.0	96.0	89.3	87.6	94.5	82.8	86.8
Moree	97.0	100	96.8	94.1	87.2	89.2	93.4	76.1
St George	96.7	100	95.1	95.3	84.7	90.4	86.2	76.3
Dirranbandi	99.0	100	100	96.4	92.4	95.7	97.6	81.0
Warren	99.0	100	100	96.4	91.4	93.7	91.1	89.3
Hillston	98.0	96.8	100	96.4	98.0	96.8	98.4	98.8
Bourke	99.0	100	100	96.4	97.0	100	97.6	92.9

* PRD signalling time= 7 days
** 3 months prior SOI values used (September – November, no lead time)
*** Rainfall disruptions amounts ≥ 10mm

Table 5.3 Probability of obtaining fourteen days of PRD signalling, for each cotton region for the period of interest (1st December- 31st January)

Soil	Sandy loam (24 days)				Heavy clay (31 days)			
Region	All years	El Nino SOI <=-5	Medium -5< SOI <5	La Nina SOI>=5	All years	El Nino SOI <=-5	Medium -5< SOI <5	La Nina SOI>=5
Biloela	64.7	81.4	62.9	48.8	46.3	61.1	43.6	33.8
Dalby	67.1	74.3	76.9	44.7	44.2	51.6	51.9	24.5
Emerald	74.9	81.6	78.8	61.8	48.9	59.0	53.5	30.9
Narrabri	87.6	94.5	82.8	86.8	67.6	75.6	60.0	70.0
Moree	87.2	89.2	93.4	76.1	68.6	79.4	68.9	56.2
St George	84.7	90.4	86.2	76.3	70.2	77.5	75.0	54.9
Dirranbandi	92.4	95.7	97.6	81.0	78.4	85.0	84.6	62.0
Warren	91.4	93.7	91.1	89.3	79.1	87.1	75.7	75.1
Hillston	98.0	96.8	98.4	98.8	91.4	95.7	89.5	89.4
Bourke	97.0	100	97.6	92.9	89.0	100	88.7	77.4

* PRD signalling time= 14 days
** 3 months prior SOI values used (September – November, no lead time)
*** Rainfall disruptions amounts ≥ 10mm

Effect of Southern Oscillation Index on successful implementation of PRD

The probability of a PRD signalling event occurring was generally reduced in La Nina years and increased in El Nino years (Table 5.2 & 5.3). This was expected given El Nino years have been found to correlate to lower annual rainfall years in much of eastern Australia (Stone, Hammer & Marcussen 1996). For northern areas (e.g.. Biloela and Emerald), the probability of producing a PRD response period was found to be higher in El Nino years when the SOI was <5 compared to median and

La Nina years (Tables 5.2 & Figure 5.1). Similarly where PRD is implemented in intermediate areas (e.g. Dalby and St George), there appeared benefit in using SOI for predicting lower rainfall seasons in El Nino years and hence higher probability of PRD signalling being achieved. However, the use of the SOI was not found to be a reliable predictor for NSW cotton growing regions (including Narrabri, Moree and Hillston) or Dirranbandi, with little or no consistent trend in probability distribution for these regions between the three main phases of the SOI (Table 5.2 & Figure 5.2).

Figure 5.1 FlowCast® probability distribution of seven day PRD signalling events in cotton based on SOI for Biloela when grown on a heavy clay soil

Figure 5.2 FlowCast® probability distribution of seven day PRD signalling events in cotton based on SOI for Narrabri when grown on a heavy clay soil

5.1.4 Discussion

5.1.4.1 Implications for the use of PRD in cotton growing regions

Southern and western cotton growing regions are more arid and have less summer rainfall than other regions. Hence, the probability of successfully implementing PRD strategies in these areas is greater (Table 5.2). The potential to implement PRD is also heavily influenced by soil type with the probabilities consistently higher for the sandy loam soil (Table 5.2). Soils with higher clay content have higher water holding capacities which result in a longer period of time required to reach the assumed deficit required to initiate the PRD response. This effect was also noted by Kriedemann (2003) as a constraint to the implementation of PRD on clay soils.

Deficit irrigation strategies are most readily implemented in regions with limited in-crop rainfall. However, there are benefits associated with implementing deficit irrigation in other regions. Regions with significant in-crop rainfall events, may have a larger potential to increase economic returns from deficit irrigation if the utilisation of the in-crop rainfall events can be optimised. Utilisation of in-crop rainfall reduces the irrigation demand and costs. Hence, deficit irrigation practices should not be limited to low rainfall regions. However, there is a need to use climatic predictors and crop modelling to identify the optimum deficit strategy for each region in each year and to evaluate the outputs within an economic framework to quantify the economic benefits.

This work has demonstrated the importance of in-crop rainfall on the identification of irrigation management strategies that can be implemented for any given year. The downside to this interaction is the increased risk when conducting a controlled irrigation strategy. For example, due to variances in rainfall between seasons, the prescription of a single deficit irrigation strategy will not result in maximising production or earliness in all seasons. Seasons with less rainfall than the average will limit yield while more rain than the average will result in sub-optimal whole farm returns from a yield limiting plant configuration and/or irrigation strategy employed. With this in mind, it is suggested that the validation and use of inter- and intra-season climatic indices should be considered in whole farm economic optimisations. Such an optimum should consider irrigation and other resource constants, the forecast conditions for the season ahead and provide a risk profile of alternative cropping/irrigation management options.

5.1.4.2 Influence of assumptions

The comparison between regions is limited by the assumptions which underpin the analysis. The period of time required to maintain PRD root zone conditions to produce (if at all) a stomatal response and a significant increase in crop water use productivity is still unknown. While the minimum period of at least a week (7 days) was arbitrarily selected, this may be an underestimate and the probability for longer periods then those calculated in Table 5.2 is further reduced as seen in Table 5.3.

Plant extraction was assumed to be constant throughout the study period. However, the extraction rate is normally variable based on crop development and climatic conditions and will be different for each region and the deficit present. The 12 mm/day rate used is consistent with the commonly recorded daily values, it seems reasonable to expect that the average rate over the entire period is likely to be smaller. Hence, the rate used in this work would tend to over-estimate field measured extraction and the period required to initiate PRD responses would be longer than indicated resulting in a decrease in the probability values calculated.

5.1.4.3 Future research

The next step in conducting this type of probabilistic forecast for PRD success by cotton region would be to address/validate the assumptions made, investigate the occurrence of stomatal response to PRD under field conditions and the period of signalling (days) that is required for a measurable/desirable response to be achieved.

The analysis used a 10 mm rainfall trigger to reset the dry-down time for PRD to start counting again. In reality, a small rainfall event (i.e. 11mm) would only have a short term interruption before dry-down could continue undisrupted on the drying side. Incorporation of a crop model to account for variable crop evaporation and a water balance model would further improve the probabilistic productions. This study investigated the probability of achieving a response to PRD during the period 1-December to 31-January. Additional studies could also be conducted to regionalise the period of interest for plant growth stage and regional conditions.

This preliminary study did not test the 'skill' associated with using SOI for each region investigated and also stated predictions for a two month period (1-December to 31 January) which is less than the period normally used (i.e three months) for forecasting when using the SOI (McClymont, D. pers. comm.). The strength of the predictive ability could be refined by assessing the 'skill' of various climatic predictors for rainfall in each of the cotton growing regions and using the most appropriate climatic predictor in each region. As well as using this predictive tool to assess the suitability of a region to the application of a deficit irrigation strategy, it may also be possible to use the most 'skilled' regional climatic predictor and crop modelling to forecast the most appropriate deficit irrigation strategy for inter- and intra-seasonal periods.

5.1.5 Conclusions

This study evaluated the soil and rainfall limitations associated with the implementation of PRD in the Australian cotton industry. In general, the lower the water holding capacity of the soil and the more arid the environment in which the cotton is grown, the greater the potential to impose PRD conditions which are not disrupted by in-crop rainfall. The predominance of heavy clay soils in the cotton industry and the location of the majority of the industry within summer rainfall areas are both likely to be major constraints to the successful application of PRD in cotton. However, the use of rainfall probability modelling and climatic predictors can improve the likelihood of predicting which areas and seasons are best suited to successfully implementing DI, RDI and PRD under commercial field conditions.

5.2 Effect of Soil-Water Movement and Irrigation Volume on the Implementation of PRD

5.2.1 Introduction

Implementation of PRD requires part (i.e. normally half) of the plant root zone to be well watered while the remaining root zone (i.e. the other half) is allowed to dry. The drying side is responsible for the AbA signalling which in turn reduces crop water use. The results from the previous glasshouse work (Chapter 3) suggested that the soil-water deficit on the dry side of the plant must reach a soil-water potential greater than 1500 kPa to produce significant signalling. Subsequent field trials (Chapter 4) to evaluate PRD in cotton under LMIMs over two seasons failed to identify any significant PRD response.

Soil-water measurements taken during the trials suggested that the appropriate root zone soil moisture conditions for triggering a PRD response may not have been met. Factors which may have influenced the root zone soil moisture include the relatively large volumes of water applied in each irrigation and the hydraulic properties of the heavy cracking clay soils. While irrigation was applied to only one side of the plant row, substantial lateral movement of soil-water (via both crack flow and matric flow) may have limited the ability to retain irrigation water on the nominally wet side of the plant without partially re-irrigating the dry side. This may have reduced both the soil potential gradient across the plant line and the ability to trigger a PRD response in the plant. Hence, it seems likely that successful field implementation of PRD will be a function of both the soil hydraulic properties and the irrigation strategy employed. This section reports on a preliminary study to predict the effect of soil hydraulic properties and irrigation strategies on the potential to create the necessary root zone soil-moisture conditions that will trigger a PRD response in cotton.

5.2.2 Methodology

5.2.2.1 Simulation model

The soil-water simulation model HYDRUS-2D (Rassam, Simunek, van Genuchten 2003) was used to evaluate a range of soil hydraulic conditions and irrigation management options. HYDRUS-2D is a soil-water model designed to simulate the movement of water flow and solute transport in two-dimensional, variably saturated media. The volume, frequency and location of water application to the soil can be varied along with the soil hydraulic properties at nodes within the computational mesh. The model also incorporates variable root water uptake, surface evaporation and rainfall input in response to weather conditions, and drainage interfaces. Outputs include the soil-water potential, content and flux at specified locations within the soil profile.

5.2.2.2 Model validation and calibration

HYDRUS-2D was parameterised using the pre-processing steps outlined in Rassam, Simunek, van Genuchten (2003) and the soil, plant and climatic parameters listed in Appendix F. The soil profile geometry was set to simulate 15 cm deep furrows on 1 m spacings with the plant row and furrow base both 20 cm wide (Figure 5.3). The simulated soil profile was 1.5 m deep and 4 m wide to enable the simulation of one fully wetted and two half wetted furrows along with two dry furrows.

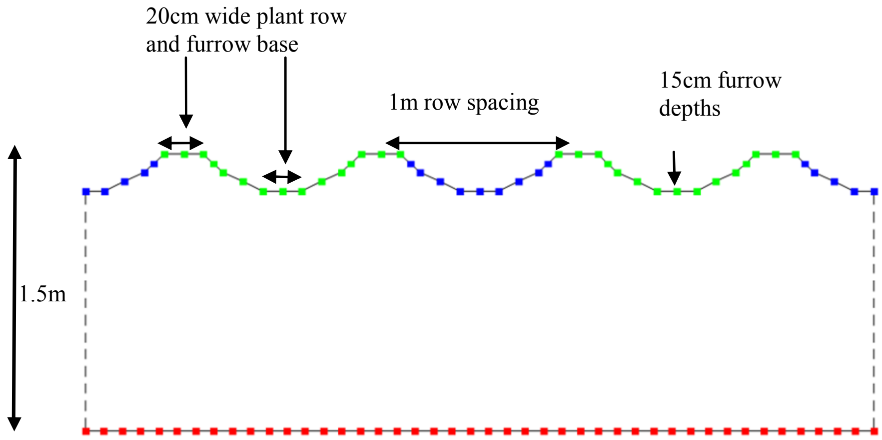


Figure 5.3 Outline of simulated soil profile and furrow configuration

Irrigation applications and the resultant soil moisture profiles obtained during the 2002-2003 'Macquarie Downs' field trial (Chapter 4) were used in the validation. The period selected was the 2nd January to the 5th March 2003 (63 days) which included four irrigation events (Table 4.2). Soil moisture measurements were taken at various intervals during the 63 day study period from a transect of four neutron moisture meter (NMM) tubes spaced 0, 33, 66 and 100 cm from the centre of the wetted furrow (Figure 4.7). NMM readings in each tube were taken at depths ranging from 200 to 1100 mm in 100 mm increments. Daily weather data for the study period was sourced from a local Bureau of Meteorology weather station.

Table 5.4 Irrigation events during validation period

Day No	Date	Irrigations (mm)
12	13/01/2003	56
18	19/01/2003	56
21	22/01/2003	61
40	10/02/2003	37

Additional soil physical parameters were required for the model operation. Values of saturated moisture content, bulk density, moisture content at field capacity and moisture content at permanent wilting point were obtained from a previous trial conducted at the study site (NRME n.d.). Particle size analysis data for the site was obtained from Goyne (2000). Surface and subsoil saturated hydraulic conductivity were obtained from an earlier hydraulic study and infiltration project conducted on cracking clay soils in the local area (Connolly *et al.* 2002, Connolly *et al.* 2001) and subsequently adjusted during calibration.

A no flux boundary was set on the vertical side boundaries of the furrow profile to stop lateral water movement into or out of the soil profile and was consistent with an assumption of soil-water potential symmetry across these boundaries. Free drainage was assumed at the base of the profile. A variable pressure head was applied to the lower 0.6m boundary of the irrigated furrows as this corresponded to the soil surface wetted by LEPA irrigation in the field trials. An atmospheric boundary was placed along the remaining soil surface to enable interactions between the soil and the atmosphere. Root distribution was assumed to be laterally uniform due to the solid crop planting which typically resulted in roots between adjacent rows overlapping in the interrow furrow. Soil-water extraction by the crop was assumed to be 40, 30, 20 and 10% for soil layers (0-10cm, 10-20cm, 20-30cm and 30-40cm) respectively.

Model validation was conducted by comparing the measured and simulated soil moisture within the profile using a correlation analysis. The soil moisture at locations 0, 33, 67 and 100 cm away from the centre line of the wetted furrow and at depths of 25 to 135 cm in 10cm increments below the plant row were compared with the soil moisture values measured in the field trials at the same locations and times (i.e. 7, 17, 26, 39, 47, 57 and 63 days) during the study period .

5.2.2.3 Evaluation of irrigation management on soil-water conditions

A variety of irrigation frequencies and volumes were simulated using HYDRUS-2D to evaluate the effect of irrigation management on root zone moisture. Irrigations were applied every 2, 4, 6 or 8 days with application volumes ranging from 20 to 70mm in each irrigation event. The same climatic data from the validation was used in the simulation study, but with rainfall omitted to maximise the potential to achieve the required soil moisture gradient. Soil moisture throughout the profile was initially set at field capacity (33 kPa). Soil surface evaporation was assumed to be a constant 1 mm/day and transpiration was set at 11 mm per day. For each irrigation interval (2-8 days) no irrigation volumes greater than the total plant extraction during the irrigation cycle were used (i.e. 6 day cycle (6x11=66) – 20, 30, 40, 50 & 60 mm irrigations applied).

The simulations were conducted for 18 to 24 days to enable the dry side to reach an equilibrium condition. Up to 24 days simulation was also found to be a reliable simulation period based on the model validation results. Soil moisture gradients were assessed as the difference between two points at a depth of 30 cm below the surface and in the middle of each furrow on either side of the plant row. Soil moisture gradients were evaluated one day before, and one day after, each irrigation event. It should be noted that the wet side of the plant row must be able to maintain plant water status for a PRD event to be triggered and distinguished from deficit irrigation. Hence, if the wet side potential was greater than 200 kPa before re-irrigation, then the plant was assumed to be suffering from deficit irrigation effects rather than a PRD effect.

5.2.3 Results

5.2.3.1 Validation of the model

The coefficient of determination between predicted and measured soil moisture contents throughout the soil profile generally declined as the period of simulation increased (Table 5.5). After seven days of simulation the R^2 value was 83% but this value decreased to 40% after 63 days. Comparison between the simulated and measured soil moisture values indicated that the simulation model generally under-predicted the soil water content.

Table 5.5 Relationship between predicted and measured soil moisture over the study period (R^2 reported as %)

Period of simulation (days)	All depths at all distances	Distance from wetted furrow (cm), at all depths				Depths (cm), at all distances		
		0	33	67	100	25-55	65-95	105-135
7	83	72	95	93	72	75	21	52
17	69	39	93	70	71	50	17	3
26	64	49	78	71	55	38	28	5
39	58	53	66	66	50	27	36	3
47	55	45	68	59	44	22	50	6
57	47	24	61	54	35	29	6	2
63	40	16	53	47	30	21	3	3

Coefficient of determination were generally higher at shallow depths (25-55cm) and intermediate distances 33 to 67cm) away from the wetted furrow (Table 5.5). For example, after 7 days of simulation the R^2 for the shallow (25-55 cm) layers was 75% but decreased to 52 % in the >105 cm layers. Similarly, the R^2 for the soil moisture at a distance of 33 and 67 cm from the wetted furrow was greater than 90% while that for soil moisture immediately beneath the wetted furrow and the adjacent dry furrow (100 cm away) were both 72%.

5.2.3.2 Evaluation of irrigation management on soil-water conditions

The largest soil moisture gradient (across the plant root zone) which still maintained the wet side of the root zone <200 kPa was only 53.2 kPa (Table 5.6). This gradient occurred during the ninth cycle of applying a small and frequent application amount (i.e. 20 mm of irrigation every two days). Larger soil moisture gradients where achieved by reducing irrigation frequencies, however the wet side of the root zone dried to a deficit greater than 200 kPa. In some cases the wet side of the root zone was drier than 200 kPa throughout the entire irrigation cycle while in other causes this zone was <200 kPa immediately after irrigation but then dried to >200kPa prior to the next irrigation event (Table 5.6 & Figure 5.4).

Table 5.6 Maximum soil moisture gradient (kPa) at 30 cm depth between wet and dry furrows over 24 day simulation period, 1 day after last irrigation event and 1 day prior to the next scheduled irrigation

Irrigation Amount (mm)	Irrigation frequency (days)[A]							
	2		4		6		8	
	After	Prior	After	Prior	After	Prior	After	Prior
20	53	46	(1222)	(3)	(1113)	(450)	(745)	(149)
30			(759)	759	[1285]	(506)	[1278]	(406)
40			(556)	4	[723]	(385)	[982]	(267)
50					(1)	(3)	[121]	(138)
60					(2)	(8)	[52]	(115)
70							0	2

[A] (value) = Wet side deficit not maintained (> 200 kPa)
[value] = Wet side deficit not maintained (> 200 kPa) by end of irrigation cycle

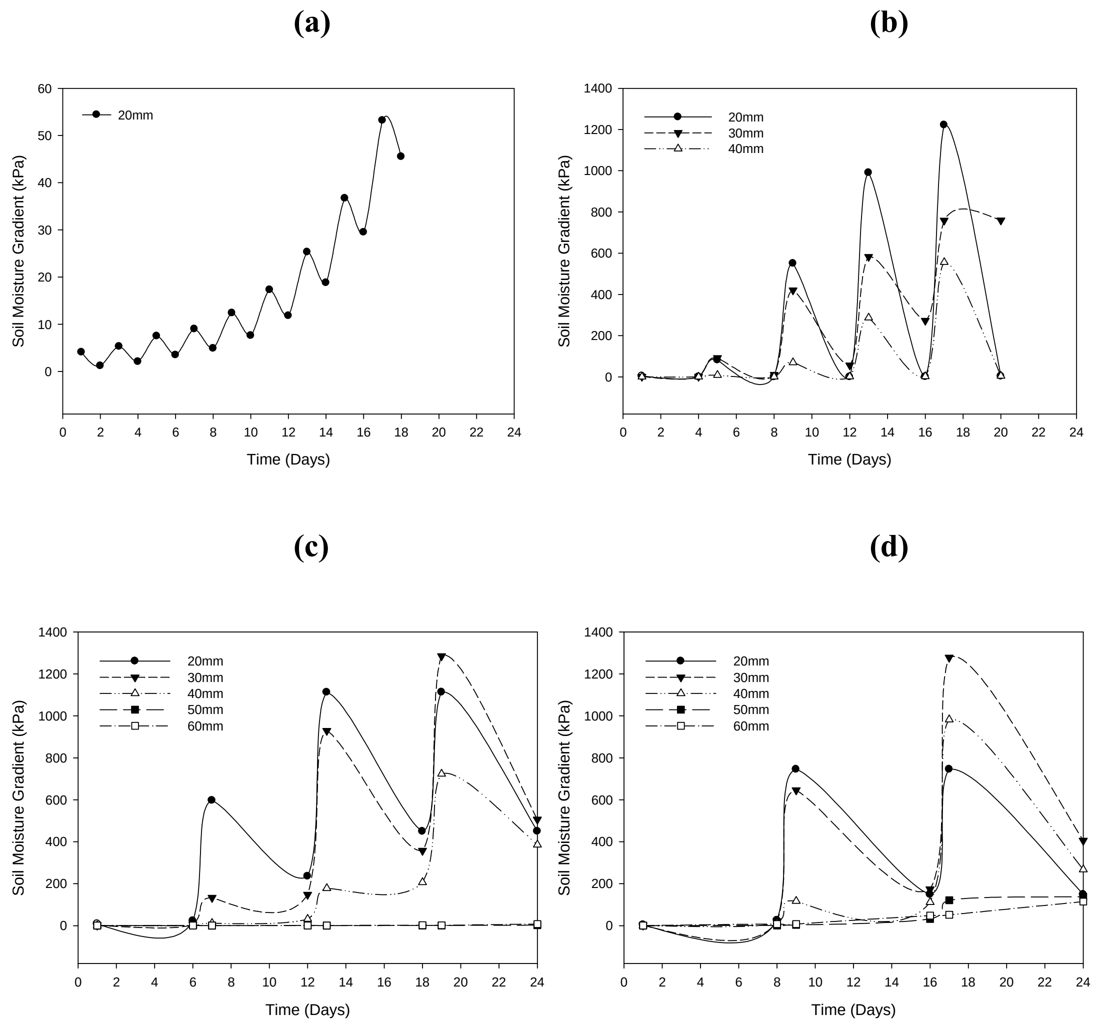


Figure 5.4 Soil water potential differences between wet and dry furrow at 30 cm depth when irrigated every (a) 2 days, (b) 4 days, (c) 6 days and (d) 8 days

5.2.4 Discussion

5.2.4.1 Validation of the model

Simulation studies using HYDRUS-2D are able to adequately predict (Table 5.5) field conditions over short periods (<26 days), across a 1 m furrow width for depths between 25-55 cm. The coefficient of determination of predicted and measured soil moisture reduced over time due to compounding errors in the soil moisture predictions. The simulated soil moisture content in the surface layers immediately under the plant row were found to be generally lower than the measured soil moisture in the field possibly due to difficulties in appropriately parameterising the root extraction pattern. Similarly, the simulated soil moisture at profile depths greater than 100 cm were under-predicted presumably due to either (a) parameterisation errors in the soil moisture characteristics (especially field capacity), or (b) the introduction of macropore (i.e crack) flow which was not able to be included in the model.

Under prediction indicated that soil moisture was less associated with increased depth. This occurrence was suggested as being due to the model not predicting irrigation water would reach that depth and that soil moisture equilibrium would be reached due to wetting and extraction some distance above this depth. In reality, the measured soil moisture differences measured at depth are suggested as being influenced by extraction at a greater depth then predicted and contributed to by macro-flow of irrigation water not parameterised for in HYDRUS-2D.

5.2.4.2 Evaluation of irrigation management on soil-water conditions

The simulations confirmed that it may be difficult to create the root zone conditions required for the triggering of a PRD response using LEPA irrigation on cracking clay soils. For the soil and irrigation conditions simulated, it was not possible to create a soil moisture gradient either large enough, or for long enough, to trigger PRD signalling. Even when irrigation volumes smaller than commonly used in commercial practice were applied on a more frequent basis, the hydraulic properties of the soil resulted in a soil moisture gradient of only 53 kPa across the plant root zone. As the soil hydraulic parameters used in this study would be expected to be similar to those for cracking clay (Vertosol soils) common throughout the cotton industry, this work suggests that it may be difficult to implement PRD on these soils using LEPA. The ability to obtain a large soil moisture gradient is a function of the clay texture which has a higher unsaturated hydraulic conductivity than the sandy soils commonly used for PRD in other crops.

Large soil moisture gradients (i.e. >500 kPa) across the plant root zone were achieved with less frequent irrigation events. However, in these cases, the deficit present on the 'wet' side root zone prior to irrigation was greater than the 200 kPa required to maintain plant water status in the desired range. In some cases, the wet side was at a deficit less than 200 kPa at irrigation but as the irrigation volume applied did not completely refill the profile on the wet side, the deficit increased beyond 200 kPa by the end of the irrigation cycle.

When water is ponded on the soil surface, infiltration occurs through both the cracks and soil matrix. The high infiltration associated with crack fill would appear to be one reason why it has not been possible to achieve a soil-water gradient under field conditions. However, when water is applied slowly to the soil (e.g. using drip irrigation), infiltration occurs primarily via matrix flow rather than crack fill. This rate of irrigation application was not evaluated in this study and the hydraulic conductivity of the soil used in the model was adjusted to mirror the field observed infiltration data which included the crack fill component. Hence, further studies are required to evaluate whether the application of water using drip irrigation systems may create the soil-moisture conditions required for PRD.

5.2.5 Conclusions

This study evaluated the ability to simulate soil water movement from measured field data and investigate the soil water potential gradient which can be achieved by applying a range of irrigation volumes and frequencies. This research has shown that LEPA irrigation is unlikely to be able to create a sufficiently large soil moisture gradient across a 1 m spaced crop row to trigger PRD signalling in cotton. Limitations in the ability to create a sufficient root zone gradient result from the inherent hydraulic characteristics of these soils and/or due to the parameterization of HYDRUS-2D. The predominance of heavy clay soils (i.e. conducive to macro-flow) in the cotton industry and application volumes commonly applied under LMIMS are likely to be major constraints to the successful application of PRD in cotton.

There remains some uncertainty over the soil-hydraulic parameters used in the model due to the presence of cracks and more extensive field evaluation of soil-water movement under LEPA socks is warranted. Similarly, the ability to apply smaller volumes of water at higher frequencies using drip irrigation systems, suggests that these irrigations may be able to create suitable root zone gradients under the appropriate conditions. Field studies to evaluate this possibility could be considered.

6.0 GENERAL DISCUSSION

This research was undertaken to evaluate the biochemical, physiological, yield and water use productivity responses of cotton associated with the application of partial rootzone drying (PRD) and deficit irrigation (DI) strategies using LMIMs under Australian growing conditions. This chapter provides a discussion of the benefits and limitations associated with PRD and DI strategies and the implications for implementing such strategies in cotton under LMIMs. It also provides recommendations for further PRD and DI research.

6.1 Partial Rootzone Drying

This research involved the first formal study to investigate the application of PRD using LMIMs in cotton. The field trials (Chapter 4) did not identify any crop growth response or yield difference due to PRD implementation. However, the results were influenced by the range of soil and climatic conditions which reduced the ability to create the soil moisture gradient (Chapter 3) required for PRD signalling. The most limiting factors were: (a) the high water holding capacity, lateral water movement and cracking nature of the soils, (b) frequency of in-crop rainfall events and (c) the volume and frequency of the commercial irrigation applications. All of these factors affect the magnitude of soil moisture gradient which can be achieved across the crop row and the period over which the gradient can be maintained.

Glasshouse studies investigating the AbA response from split-pot grown cotton (Chapter 3) demonstrated that an elevation in AbA signalling does occur due to PRD. However, high levels of soil moisture drying are required to significantly increase xylem sap AbA levels under PRD in cotton. This suggests that if the practical limitations to field implementation of PRD can be overcome, the application of PRD root zone conditions may trigger a plant AbA response. However, it is not clear that this will necessarily produce a benefit in terms of cotton crop water use productivity.

The rainfall and soil-water modelling (Chapter 5) suggested that only a small proportion of the current Australian cotton industry has a climate and soil suitable to successfully implement PRD. These areas are located in the more semi-arid regions with low in-crop rainfall events and lighter textured soils. Small, frequent irrigation applications possible with only LMIMs or drip irrigation systems would need to be applied to create the necessary conditions. Using drip for the application of PRD would require double drip lines and in a broad acre field crop such as cotton, the marginal economic benefits of PRD implementation would need to be considered.

Several concerns still remain regarding the potential for crop water use productivity improvements from the implementation of PRD in cotton. It is now known that imposing PRD root zone conditions in cotton produces elevated AbA levels in the xylem sap. However, no reduction in stomatal response or vegetative growth was found in this work (Chapter 3). This may have been due to the low evaporative conditions present in the glasshouse, the lack of sap alkalinisation and/or the cotton physiological and biochemical processes to soil drying conditions. The field trials (Chapter 4) were unsuccessful in identifying a crop response to PRD most likely due to the inability to consistently create an adequate soil moisture gradient. Practical limitations under field conditions reduced the soil moisture gradient achievable. Hence, it is still not clear whether the application of

PRD under field conditions will cause a reduction in vegetative growth and stomatal reductions due to elevated AbA similar to that observed in other crops (Comstock 2002, Davies, Wilkinson & Loveys 2002, Snaith & Mansfield 1982, Zhang & Davies 1990). However, if a benefit is found in cotton, then there are still concerns over the ability to create the appropriate soil-water gradients economically in cotton under field conditions.

Further research investment into the water use productivity benefits associated with PRD within the Australian cotton industry may be difficult to justify due to the soil and climatic limitations found in the industry. At best, if a water use productivity benefit was found from PRD the implications from this work are that only a very small area of the current industry could commercially implement the strategy under LMIMs and potentially obtain benefits. By comparison, deficit irrigation has been found to offer significant benefits to the cotton industry in terms of improved $IWUI_{Applied}$ and GPWUI. The deficit irrigation strategy employed is also influenced by in-crop rainfall events but is less affected by the frequency of rainfall events. Similarly, the benefits of deficit irrigation are less affected by the soil properties.

6.2 Deficit Irrigation

Improvements in $IWUI_{Applied}$, GPWUI and crop agronomic management in cotton were achieved by applying deficit irrigation strategies using LMIMs (Chapter 4). However, optimisation of any irrigation strategy requires an understanding in relation to crop response to irrigation and other external environmental conditions. Deficit irrigation requires the maintenance of the root zone soil moisture within a desirable range for agronomically optimal partitioning between vegetative and reproductive growth and improved water use productivity. Both the field (Chapter 4) and glasshouse (Chapter 3) trial results support previous work by confirming the reduction in vegetative growth in favour of reproductive development with increasing deficit applied (Bhattarai *et al.* 2003, Bordovsky *et al.* 1992, Hutmacher & Keeley 2001, Yazar, Sezen & Sesveren 2002). The field trials also demonstrated the significant improvement in $IWUI_{Applied}$, GPWUI and crop earliness which can be achieved over current commercial practice from greater manipulation of soil moisture conditions.

Maximum GPWUI was achieved in the field trials when approximately 80% of crop ET was replaced. This is consistent with previous deficit irrigation research on cotton with LEPA under LMIMs (Bordovsky *et al.* 1992, Yazar, Sezen & Sesveren 2002) and with drip irrigation (Bahrun *et al.* 2002, Bhattarai *et al.* 2003). However, factors other than soil moisture deficit also affect cotton's ability to grow, produce and retain fruit and achieve a given level of yield and water use productivity including: variety, plant density, nutrition, insect pressure, growth management, climatic conditions (e.g. radiation, temperature, wind and rainfall) and season length. It is unlikely therefore that one prescript level of deficit will be found that achieves the desired plant architecture, vegetative growth rate, carrying capacity, earliness, water use productivity improvement and yield for all seasons, regions, soil types and varieties.

The southern and western regions of the cotton industry with semi-arid growing conditions are best suited to regulated deficit irrigation strategies. The low in-season rainfall in these areas provides more opportunity to manipulate and maintain the appropriate soil moisture conditions during the season. However, regions with significant in-crop rainfall events have a greater potential to improve $IWUI_{Applied}$ through the use of supplementary irrigation strategies. This is due to the benefits associated with improved timing of irrigations applied in co-ordination with rainfall events (maximising in-crop rainfall capture) and improved capture of rainfall by maintaining the soil moisture at a deficit.

6.3 Implications for the Industry

A significant PRD response in terms of elevated stem sap Abscisic Acid was found to occur (Chapter 3) in cotton. However, this did not produce a measurable change in stomatal conductance under the relatively low evaporative conditions within the glasshouse environment. Plant physiological responses (e.g. plant height and number of fruiting branches) were found between alternated PRD, non-alternated PRD and RDI strategies. However, plant responses due to PRD signalling could not be separated from the effects of RDI.

Deficit irrigation under field conditions produced significant $IWUI_{Applied}$ and GPWUI benefits. However, there was no water use productivity benefit associated with PRD under the soil and climatic conditions experienced. The frequency and volume of in-crop rainfall has a major influence on the ability to implement PRD and RDI and the benefits arising from these strategies. The conditions required to implement PRD are more restrictive due to the larger soil drying requirement and the need to maintain a soil moisture gradient across the root zone

The glasshouse (Chapter 3), field (Chapter 4) and preliminary modelling work (Chapter 5) undertaken to investigate the use of PRD and DI in cotton under LMIMs have identified a number of implications for industry and their use including:

- Although a significant biochemical response from PRD can occur in cotton, no evidence of an agronomic or water use productivity benefit from PRD under field conditions has yet been found.

- To achieve a PRD response in cotton requires the presence of a significant soil moisture gradient. For cotton grown on cracking clay soils in summer rainfall zones the application of high frequency, low volume application using LEPA systems will not create the soil moisture gradient required for PRD signalling to occur.

- Root zone soil moisture conditions required for PRD are most likely to be successfully applied on light textured soils in the southern and western regions of the cotton industry which have minimal in-crop rainfall.

- Significant improvements in $IWUI_{Applied}$ and GPWUI can be achieved with deficit irrigation strategies and it should be possible to successfully apply deficit irrigation across the majority of the Australian cotton industry.

- Further research integrating a validated crop model, whole farm water balance and location specific climatic conditions is required to identify the most appropriate deficit irrigation strategies to employ under a range of conditions.

This work suggests that PRD is not able to be successfully applied in many areas of the cotton industry due to soil and climatic limitations. Similarly, the benefits from implementing PRD do not appear to be significant in cotton. Hence, it is difficult to justify further significant investment in investigating the application of PRD in cotton. However, deficit irrigation is well suited to the cotton industry and holds the potential for significant improvements in crop water use productivity. The optimal deficit irrigation strategy to employ is likely to be seasonally (i.e. rainfall probability, water availability) and regionally (i.e. climatic and soil variables) dependent and further research is required to identify appropriate strategies.

6.4 Recommendations for Further Research

This research has raised a number of questions which could be addressed in future studies including:

- Can a biochemical and/or physiologically beneficial response to PRD root zone conditions be achieved (i.e. when PRD is successfully implemented and maintained) under field conditions? If so, what proportion of the current cotton industry can commercially implement PRD successfully and achieve the associated benefits found? However as previously stated further significant investment is not justified.
- What is the most appropriate method of scheduling deficit irrigation practices under LMIMs with LEPA socks given the high spatial variability in soil moisture movement?
- What is the best deficit irrigation strategy for each region and season and how will this change based on individual grower resources? What economic rational can be used to decide on the best deficit strategy to employ for each season and how can the performance of a crop be tracked intra-seasonally with a target crop yield/deficit strategy chosen?

6.4.1 Biochemical and Physiological Effects of PRD under Field Conditions

Future evaluations of the biochemical and stomatal responses of cotton to PRD should be conducted under field conditions. Atmospheric evaporative conditions will have a major influence on the stomatal conductance response to AbA signalling. Hence, to ensure that all potential responses are observed, future studies will need to empirically quantify the presence of root to shoot signalling (AbA, sap pH and any others), its delivery to sites of action and its influence on stomatal response and vegetative growth under field comparable climatic conditions. However, this will require the investigators to overcome the practical limitations associated with the application of PRD under field conditions. This would necessitate the use of a rainout shelter to exclude in-crop rainfall interferences. Similarly, a physical barrier could be placed within the root zone to stop lateral soil moisture movement and improve the potential to create the required soil moisture gradient. Diurnal assessment of plant water status would also be required to ensure conditions and responses found are able to be directly attributed to PRD rather than deficit irrigation conditions. More detailed rainfall and soil moisture modelling should be conducted to better define the irrigation management conditions (e.g. irrigation frequency and volumes) required to implement PRD.

6.4.2 Scheduling under Deficit Irrigation Conditions

The high variability in root zone soil moisture conditions experienced under deficit irrigation applied by LEPA socks demonstrated limitations in the use of point source soil moisture sensors for scheduling under these conditions. An alternative scheduling system such as a water balance approach or the use of plant based sensors for irrigation scheduling is required. However, further research is required to validate and calibrate plant based sensors under a range of conditions (e.g. deficits, evaporative demands, irrigation history) for irrigation scheduling within the cotton industry.

6.4.3 Identifying Optimal Deficit Management Strategies and Economic Options

Improvements in water use productivity were found through the implementation of deficit irrigation treatments during field trial work. However, irregularity in the occurrence, timing and amount of in-crop rainfall as well as other climatic factors will limit the success of a prescription application of deficit irrigation for cotton in a majority of the industry. To add to this is the difference in resources available such as land and irrigation water between individual farms. Personal attitude in farmers' adversity to risk (function of financial position and previous experience) will also influence the choice of a given irrigation strategy employed. Hence, there is also a need to evaluate the farm financial returns associated with implementation of various deficit strategies under a range of farm resource limitations.

The identification of appropriate deficit irrigation strategies in cotton under LMIMs will require a suitably robust and validated crop model which incorporates climatic predictions and the assessment of individual grower resources. This model framework would enable not only inter-season forecasting but could also be used as an intra-season management tool to evaluate crop performance in comparison to simulated performance indicators. At season end this can also be used to assess the crops performance in comparison to the simulated crop. The result would be a probability/risk analysis strategy to generate for a given season, region and given grower irrigation strategy options. This would enable the grower to select their preferred level of risk for a given predicted economic return to assets. The commercial realization and application of irrigation practices such as deficit and regulated deficit irrigation in cotton production would require the collaborative efforts of various research disciplines including soil scientists, plant physiologists, climatologists, plant breeders, crop modellers and economists.

A validated crop production model which evaluates a range of irrigation scheduling options in terms of predicted return on investment and outputs options in terms of a given level of financial (cropping) risk is required. The use of regionally skill tested climatic predictors within the crop model should also assist in reducing the uncertainty associated with the implementation of deficit strategies. This may make the decision to adopt deficit irrigation practises for greater economic return more attractive (i.e. increased return but lower risk). This is an important factor to consider in determining the adoption of improved irrigation practises in light of the general risk adversity amongst the farming community.

7.0 CONCLUSION

This study has identified the benefits and limitations of PRD and deficit irrigation for cotton grown using centre pivots and lateral moves under Australian conditions. The biochemical, physiological, yield and water use productivity responses associated with PRD and deficit irrigation strategies have been quantified and the industry implications associated with implementing these strategies identified. Glasshouse trials were conducted to investigate the physical and biochemical responses of cotton to irrigation strategies without field constraints (Chapter 3). Field trials implementing a range of deficit and PRD irrigation treatments were conducted using a centre pivot and lateral move to measure crop response, yield and water use productivity under commercial conditions (Chapter 4). Modelling of soil moisture movement and rainfall probability were also conducted to quantify the soil and climatic limitations to commercial implementation of PRD and deficit irrigation (Chapter 5).

PRD applied to cotton grown in split-pot containers in a glasshouse environment produced a four fold increase in xylem Abscisic Acid concentration when the soil-water potential was greater than -1500 kPa (Chapter 3). Crop growth responses (i.e. plant height and fruiting sites) were also produced when PRD was applied to the split-pot grown cotton plants. However, it was not clear whether these growth responses were due to biochemical signalling associated with PRD, due to a hydraulic response associated with deficit irrigation, or a combination of both processes.

There was no significant response in crop growth or yield associated with PRD conditions applied to cotton grown using a commercial centre pivot and lateral move (Chapter 4). However, the lack of plant response observed may have been due to the inability to apply and maintain a PRD soil-water gradient given the soil hydraulic properties, irrigation practices (i.e. volume and frequency of water applied) and in-season rainfall experienced.

Probabilistic analyses and soil moisture modelling (Chapter 5) indicated that PRD could only be successfully applied on a small area of the current Australia cotton industry. The most likely areas to be able to implement PRD are those with light textured soils located in the southern and western regions which have a semi-arid climate and experience infrequent in-season rainfall. Small, frequent irrigation applications achievable only with either drip irrigation or LMIMs would also need to be applied. On this basis, further research work into the agronomic and water use productivity benefits associated with the application of PRD in the Australian cotton industry is unwarranted. However, if further research is contemplated, efforts should be focused on (a) strategies to create the necessary root zone soil-moisture gradient and (b) quantifying the growth and yield responses under field conditions.

Regulated deficit irrigation applied under glasshouse conditions was found to have a controlling influence over partitioning between vegetative and reproductive growth (Chapter 3). Field trials (Chapter 4) demonstrated the ability to improve $IWUI_{Applied}$ and GPWUI and maintain crop yield by applying deficit irrigation strategies using LMIMs. The largest benefits derived from deficit irrigation were associated with the management of crop agronomics (i.e. vegetative growth, retention rate and crop earliness) and the increased ability for capture of in-crop rainfall. Supplementary in-crop rainfall is important in the crop growth response, yield and water use productivity for any given deficit irrigation strategy applied.

Deficit and regulated deficit irrigation strategies are already inadvertently applied within the Australian cotton industry as many LMIMs have inadequate capacity to meet peak irrigation water requirements. Some irrigators have also adopted irrigation strategies which maintain a soil moisture deficit to avoid waterlogging and water stress. The optimum prescription application of deficit irrigation will vary according to the prevalence of in-crop rainfall and climatic growing in different regions. Similarly, the optimum level of stress and the timing of deficit applied will be seasonally dependent on irrigation resources, yield goal, weather conditions, economics of production, current crop development, the level of 'stress' pressures and individual grower risk levels. Hence, successful deficit irrigation requires a thorough understanding of a crop response to imposed deficits and forecasting of rainfall occurrence for the season ahead. A suitable validated crop model and the use of skill tested climatic indicators is needed to ensure the optimal deficit strategy is employed in any given season and region.

Future research should aim to enhance current crop production models to predict crop growth and response to a range of deficit irrigation treatments and strategies. Greater knowledge and adoption in the use of climatic predictors (such as SOI) are required to improve the volume and timing of deficit irrigations applied. An economics framework needs to be developed which encompasses all resource costs and constraints on a per farm basis to enable a risk profile of all deficit irrigation strategies to be assessed. Sufficient training of support staff such as irrigation consultants would also be required to gather, collate and present this whole farm economic water use productivity risk profile to growers and assist in its adoption inter and intra season.

In the short-term, further quantification of field variability due to soil moisture conditions and the assessment of alternative irrigation and agronomic tools (plant based sensors, spatial and temporal remote sensing) to monitor and manage field variability for deficit irrigation scheduling requires investigation.

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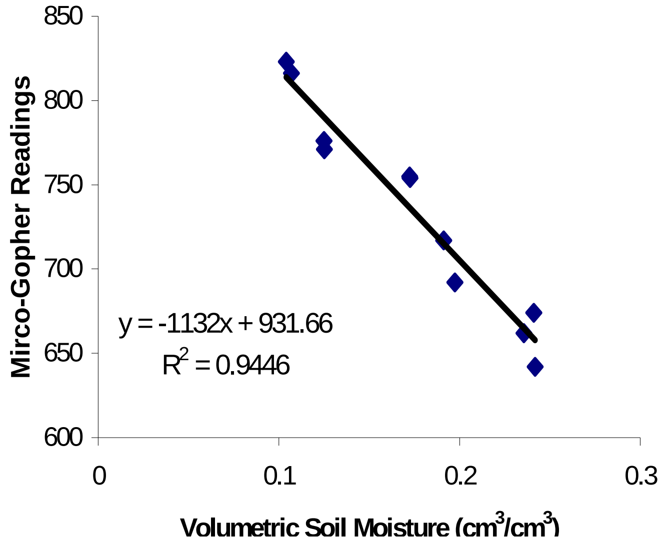
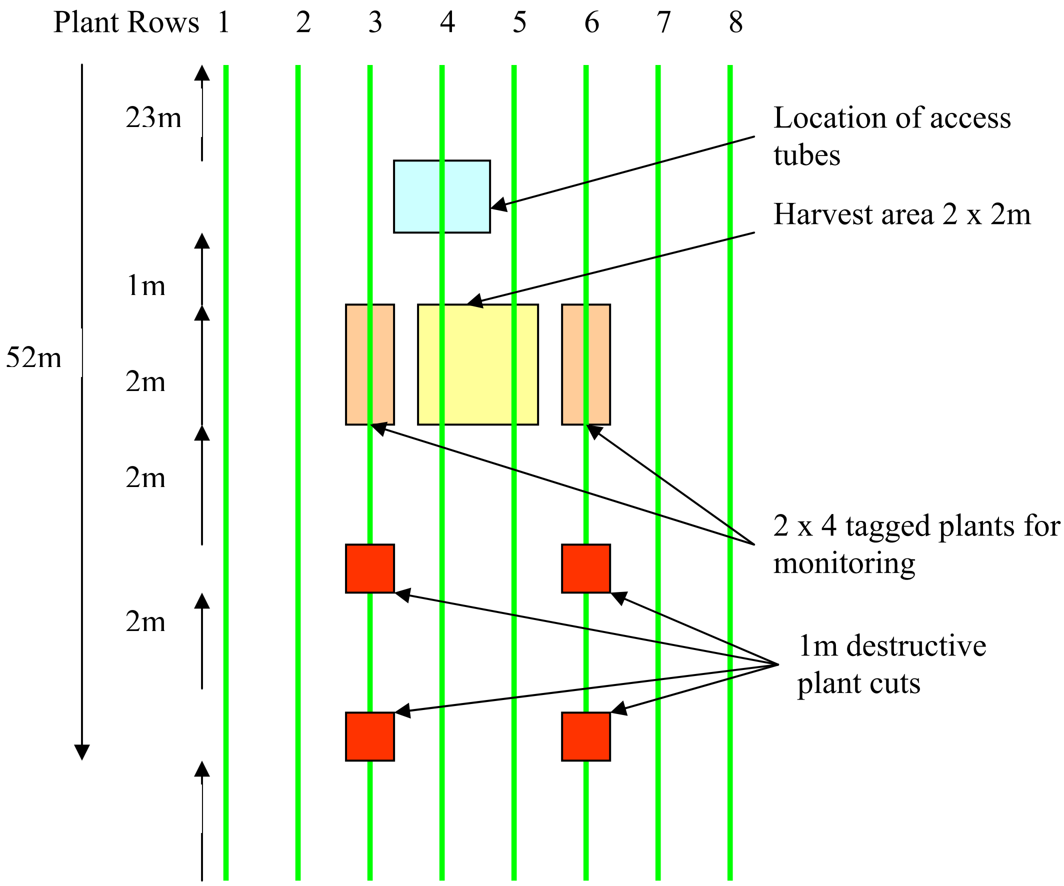
Appendix A. Calibration curve for Micro-Gopher

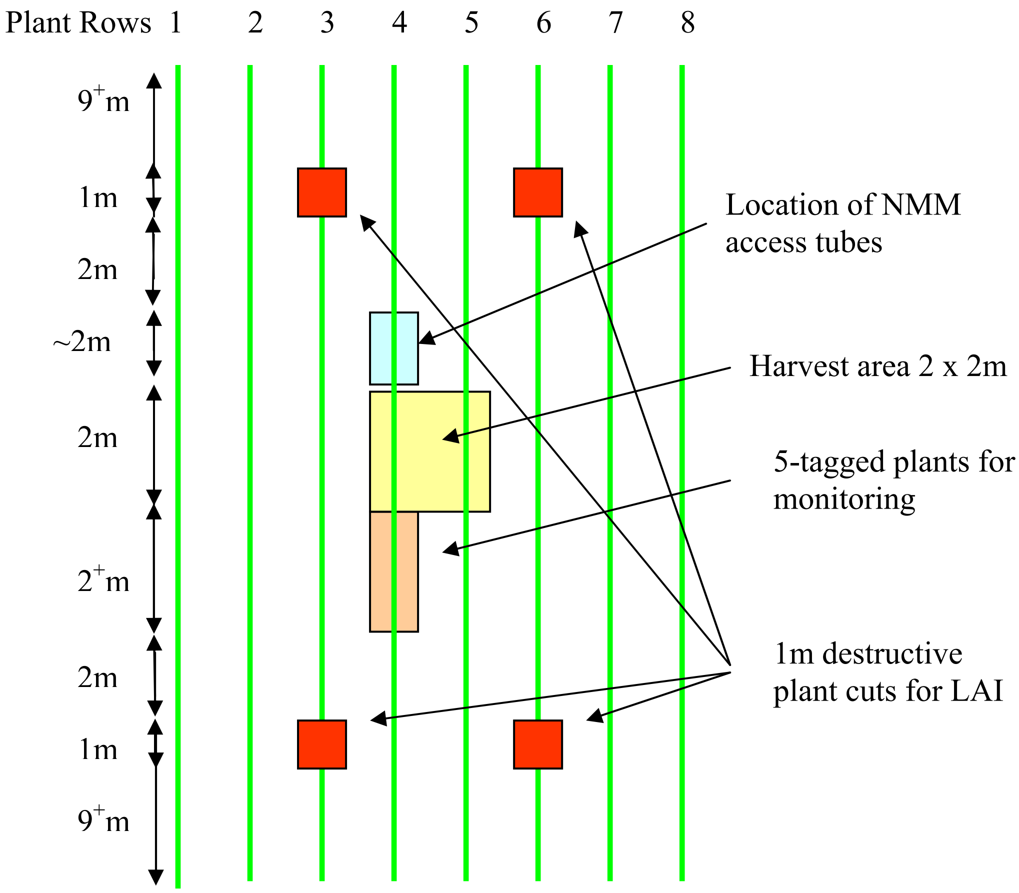


Appendix B. Geofabric use in pot bases showing root intrusion

Appendix C. **Plot layout, 'Macquarie Downs' (2002/2003)**



Appendix D. **Plot layout, 'Rainbow Valley' (2003/2004)**

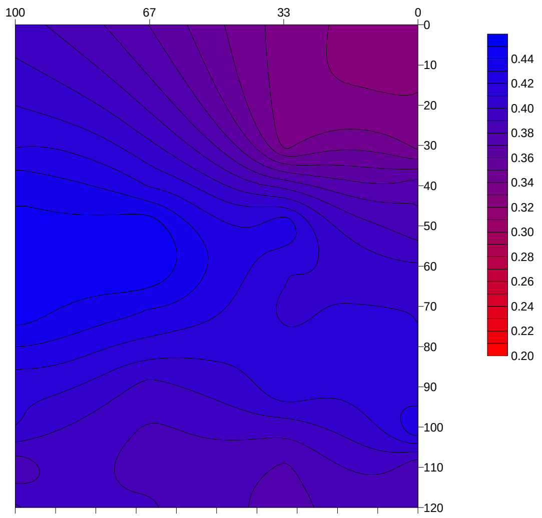


Appendix E. Volumetric soil moisture, 'Rainbow Valley' (2002/2003)

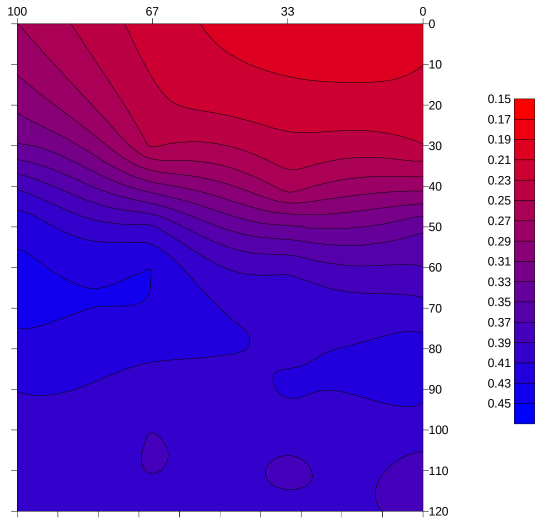
Tubes were located across the plant row at 0, 33, 66 and 99cm
Soil depth is presented from 0-120cm measured from base of furrow
Soil moisture measurements were taken at 30-120cm, 0-30cm was extrapolated
Soil moisture is presented as estimated volumetric %
Arrows denote furrow side previous irrigation by LEPA was applied to (multiple arrows denotes post sprinkler irrigation).

<u>Plot 3 (75% Non-Alt)</u>

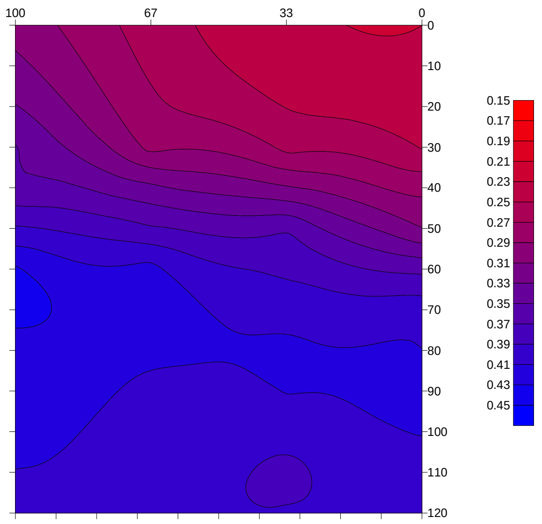
23/12/2003 0000
(7 days before 1st irrigation)



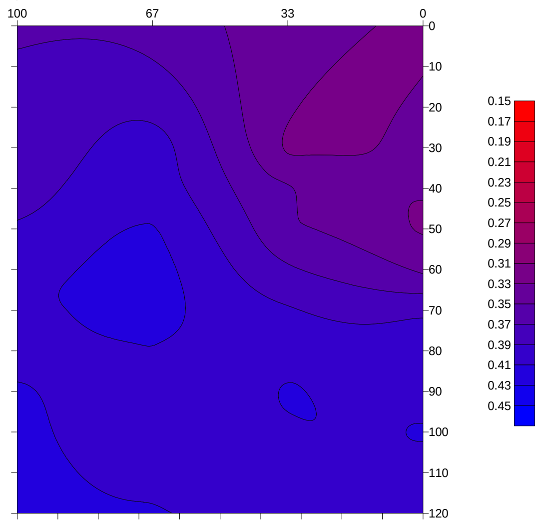
31/12/2003 1610
(6 hrs before 1st irrigation)



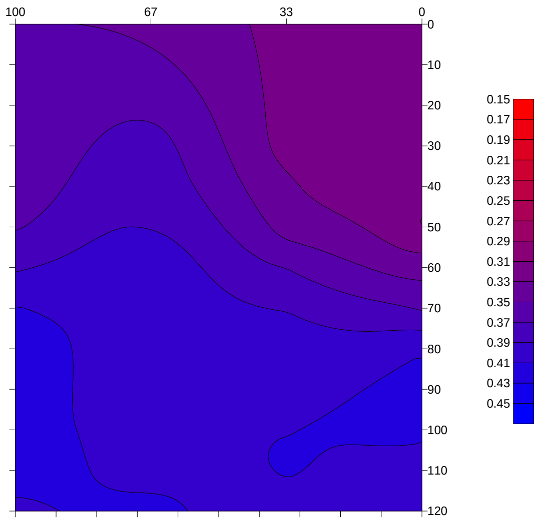
6/1/2004 2100
(3 hrs before 2nd irrigation)
↓



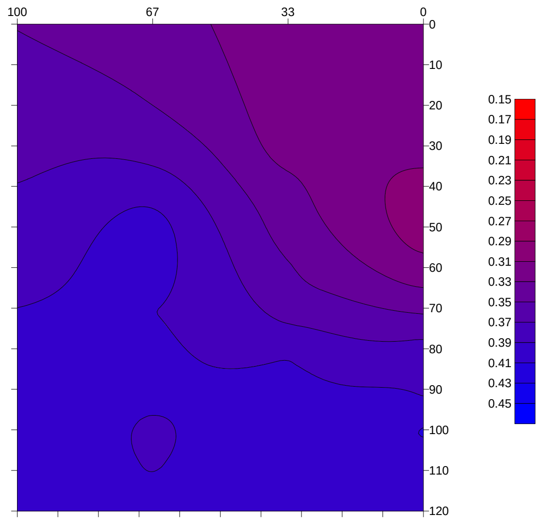
21/1/2004 1704
(14 days after 2nd irrigation + 150mm)
↓



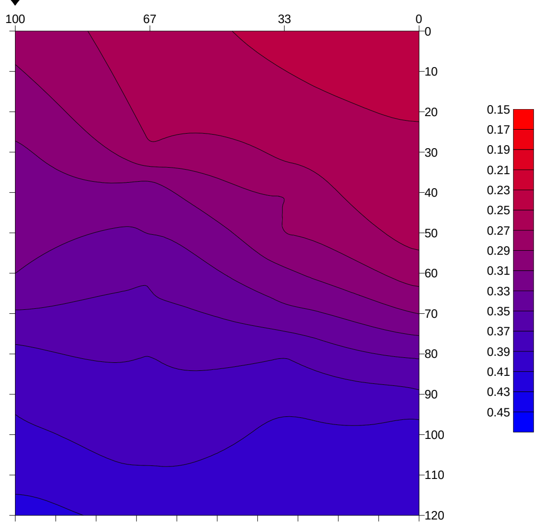
23/1/2004 1722
(16 days after 2nd irrigation + 150mm)



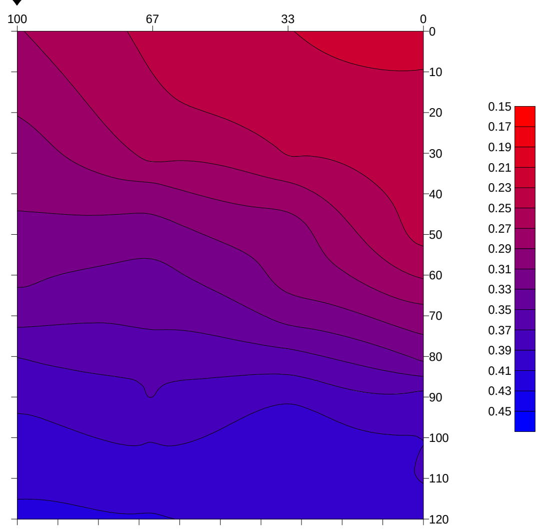
9/2/2004 1550
(6 days before 3rd irrigation)



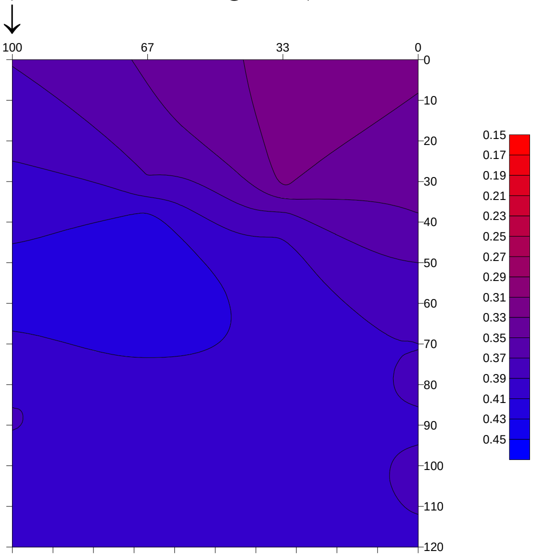
13/2/2004 1438
(2 days before 3rd irrigation)



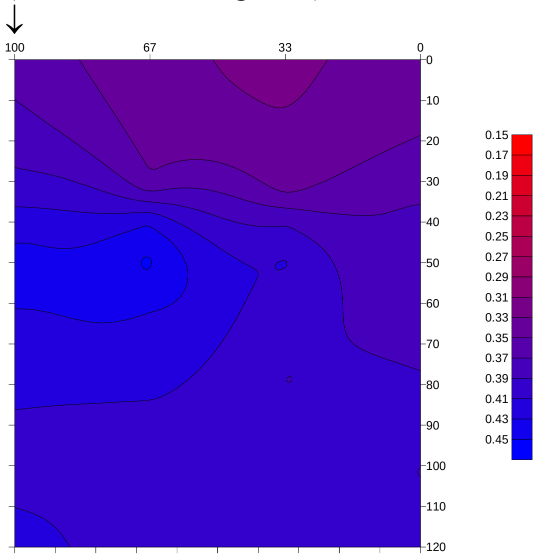
15/2/2004 0740
(4 hrs before 3rd irrigation)



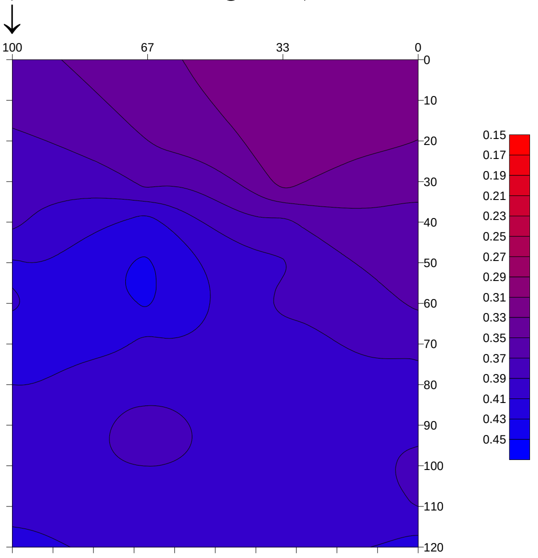
15/2/2004 1220
(½ hr after 3rd irrigation)



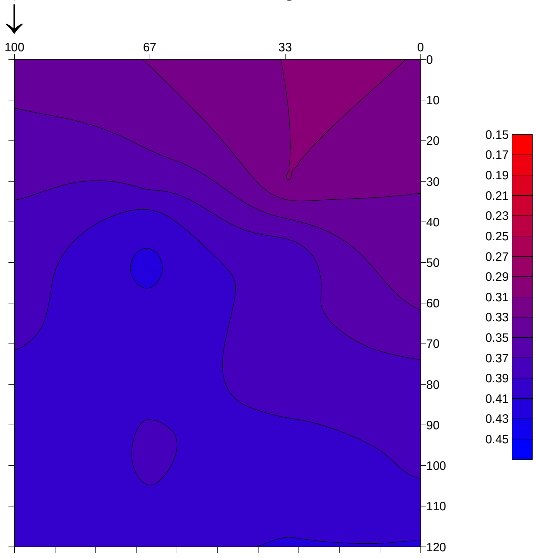
15/2/004 1340
(2 hrs after 3rd irrigation)



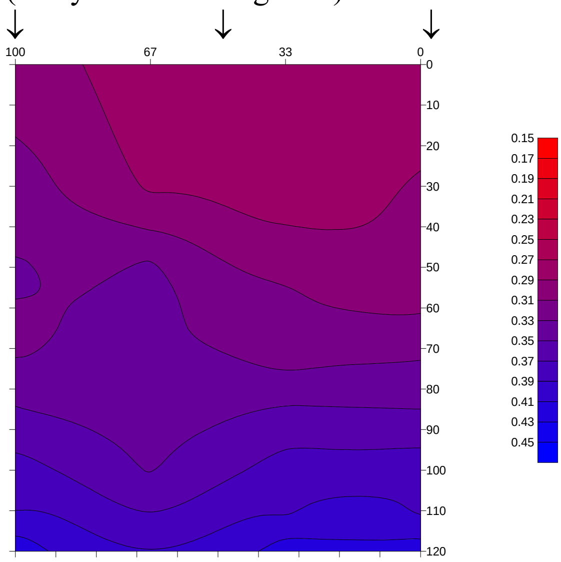
15/2/2004 1843
(7hrs after 3rd irrigation)



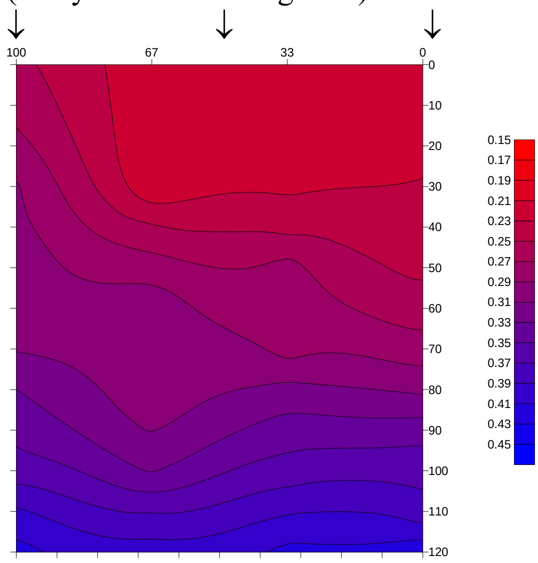
16/2/2004 1806
(30 ½ hrs after 3rd irrigation)



27/2/2004 1402
(8 days after 4th irrigation)

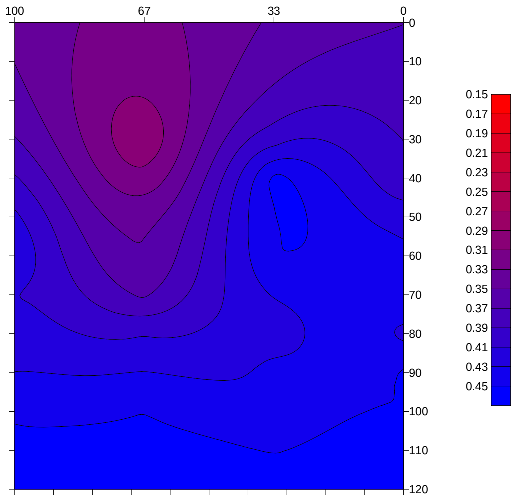


2/3/2004 1400
(2 days before 5th irrigation)

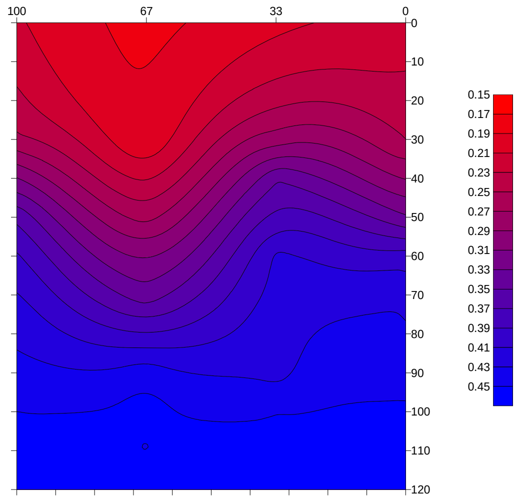


<u>Plot 7 (75% Non-Alt)</u>

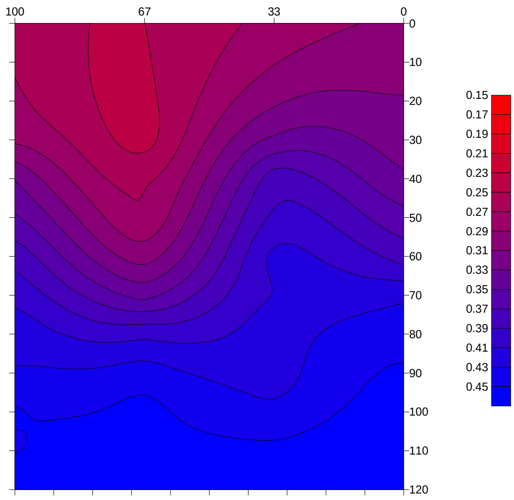
23/12/2004 1445
(7 days before 1st irrigation)



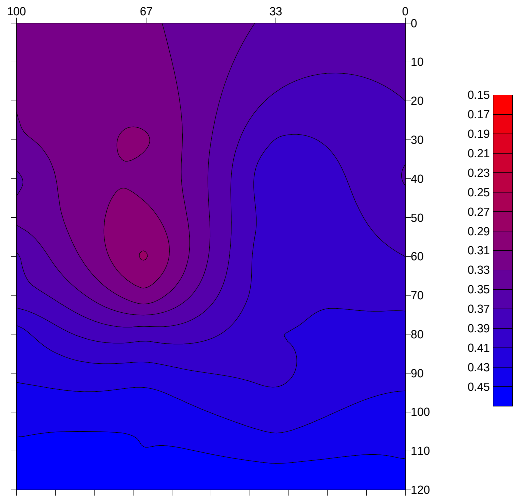
31/12/2004 1637
(10 hrs before 1st irrigation)



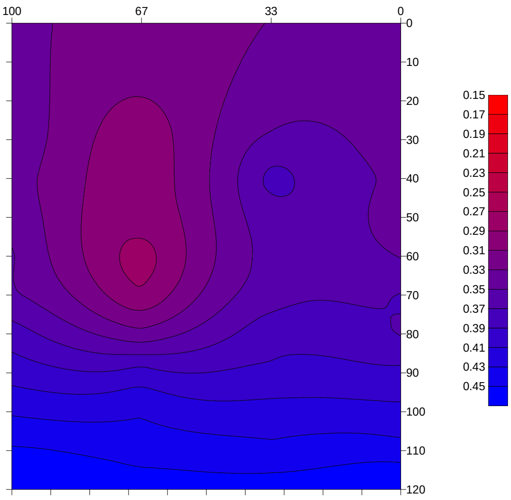
7/1/2004 0128
(3 ½ hrs before 2nd irrigation)
↓



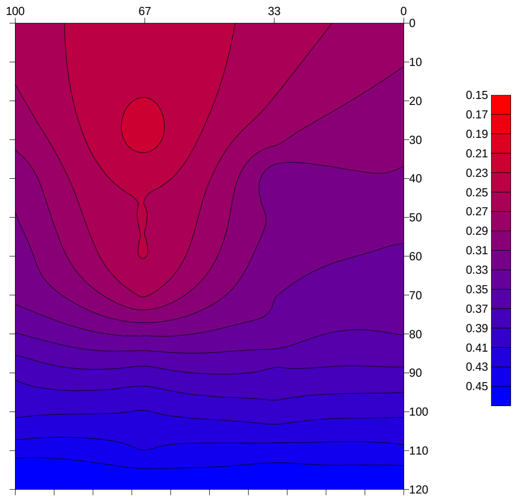
23/1/2004 1800
(16 days after 2nd irrigation + 150mm)
↓



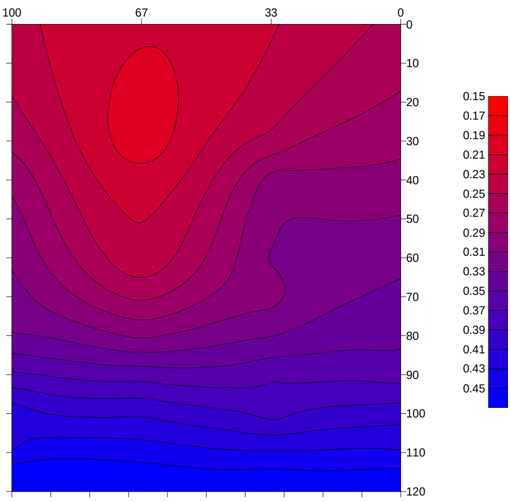
9/2/2004 1641
(6 days before 3rd irrigation)
↓



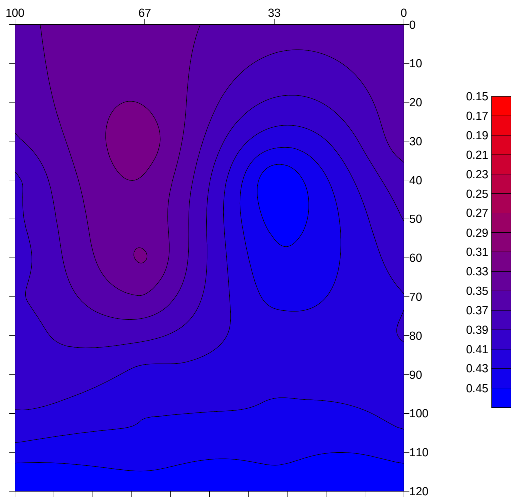
13/2/2004 1537
(2 days before 3rd irrigation)
↓



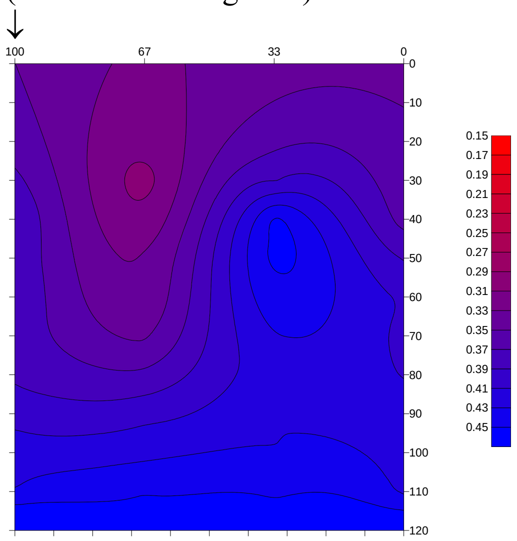
15/2/2004 1406
(2 hrs before 3rd irrigation)
↓



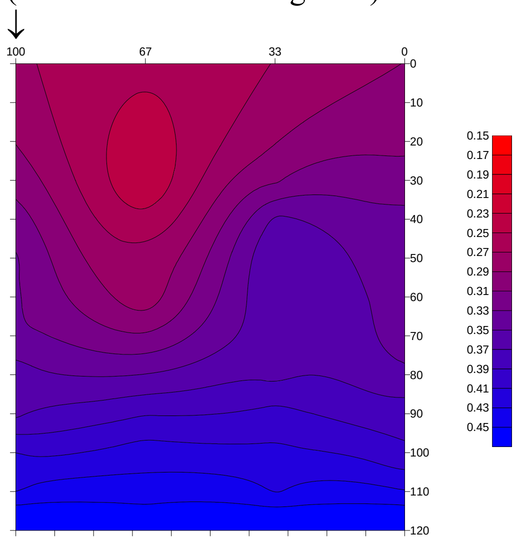
15/2/2004 1627
(½ hr after 3rd irrigation)
↓



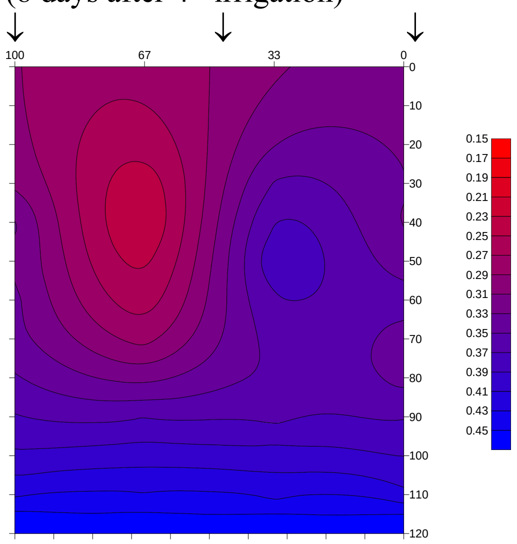
15/2/2004 1804
(2 hr after 3rd irrigation)



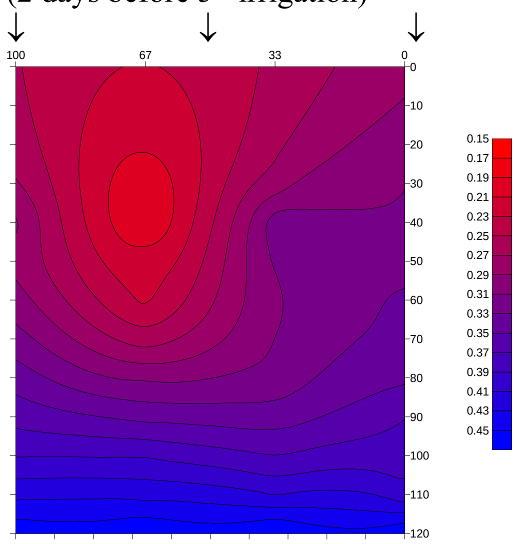
19/2/2004 1703
(3 ½ hrs before 4th irrigation)



27/2/2004 1639
(8 days after 4th irrigation)

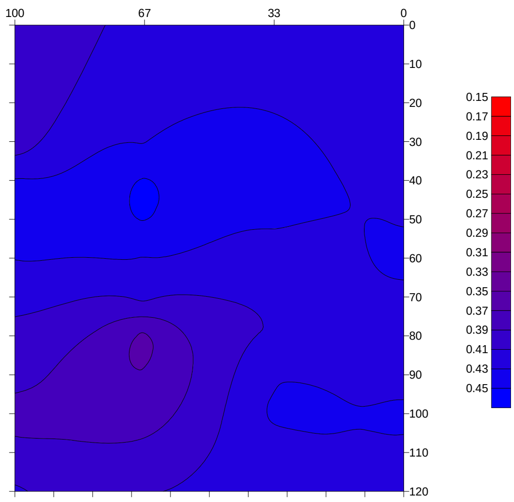


2/3/2004 1436
(2 days before 5th irrigation)

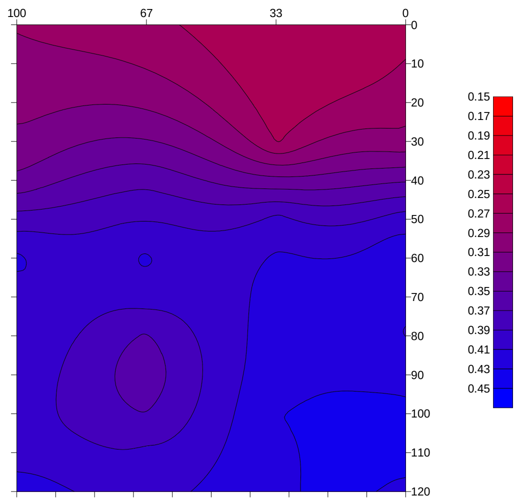


Plot 5 (75% Alt. every)

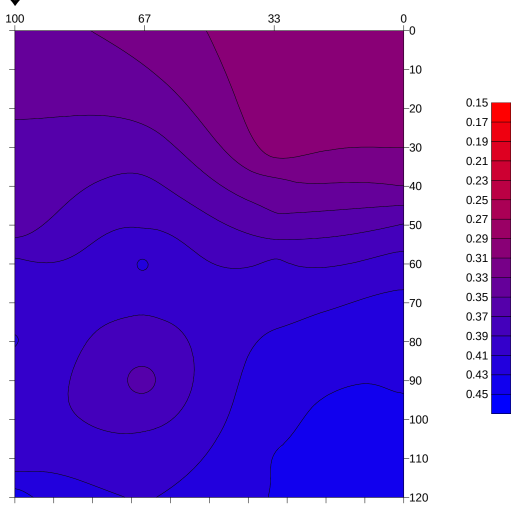
23/12/2003 1445
(7 days before 1st irrigation)



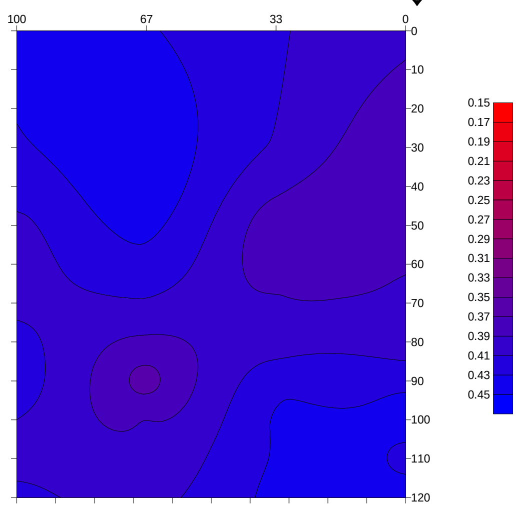
31/12/2003 1624
(8 hrs before 1st irrigation)



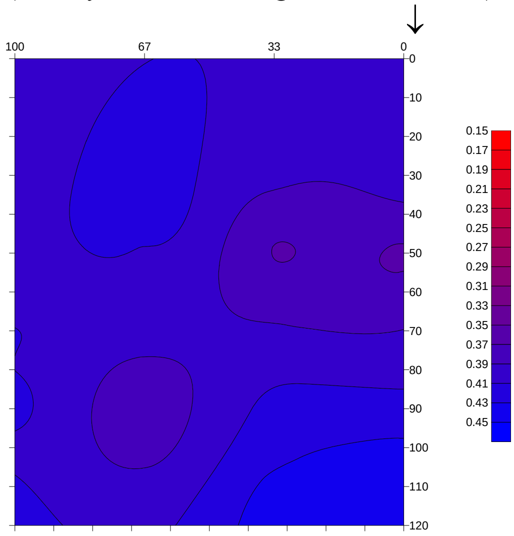
6/1/2004 2310
(3 ½ hrs before 2nd irrigation)
↓



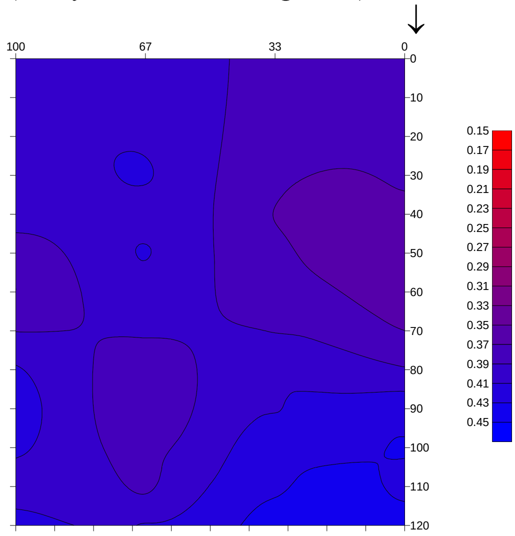
21/1/2004 1729
(14 days after 2nd irrigation + 150mm)
↓



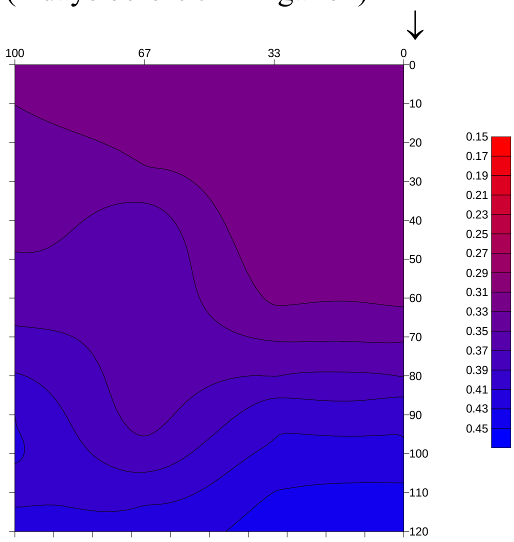
23/1/2004 1749
(16 days after 2nd irrigation + 150mm)



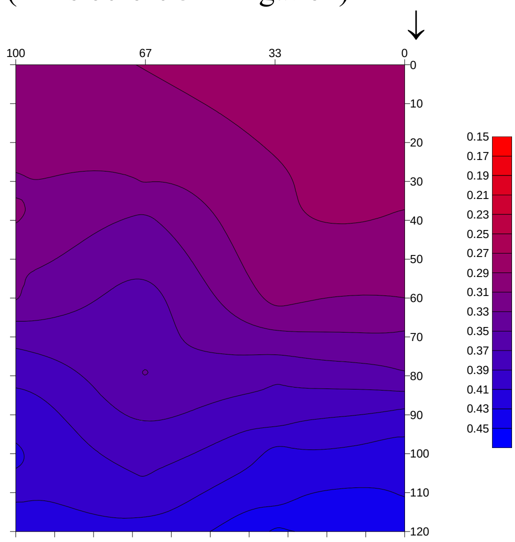
9/2/2004 1612
(6 days before 3rd irrigation)



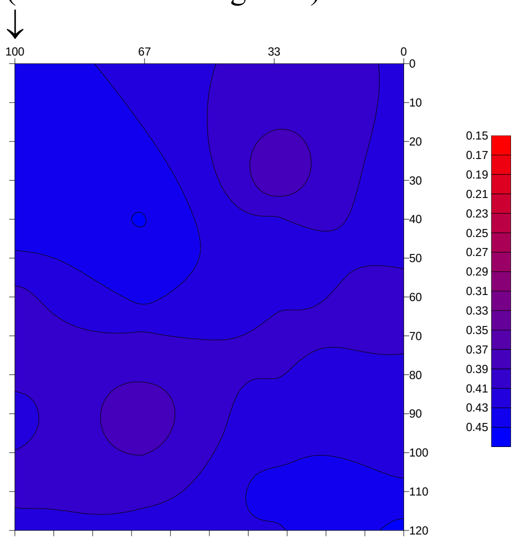
13/2/2004 1501
(2 days before 3rd irrigation)



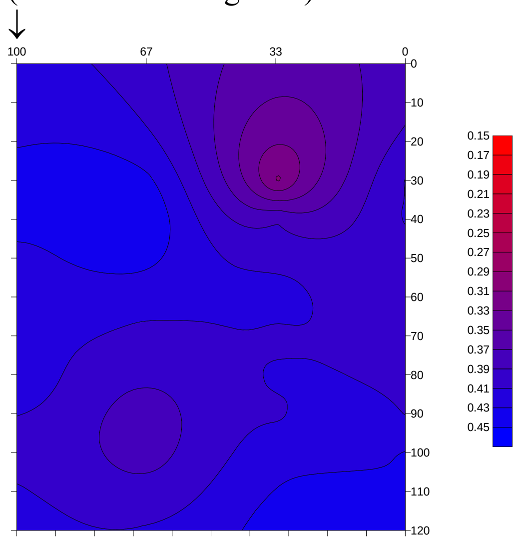
15/2/2004 1200
(2 hrs before 3rd irrigation)



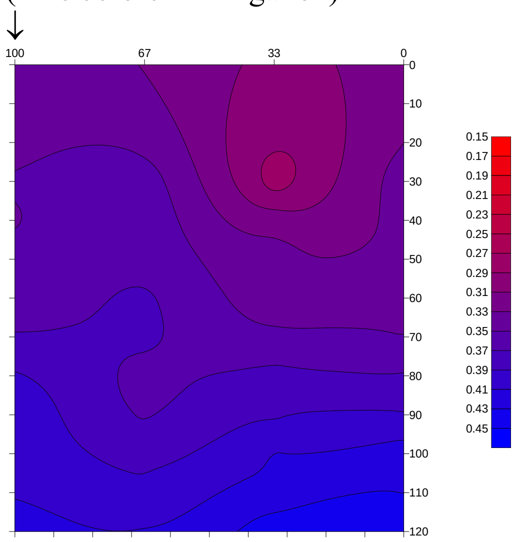
15/2/2004 1426
(½ hr after 3rd irrigation)



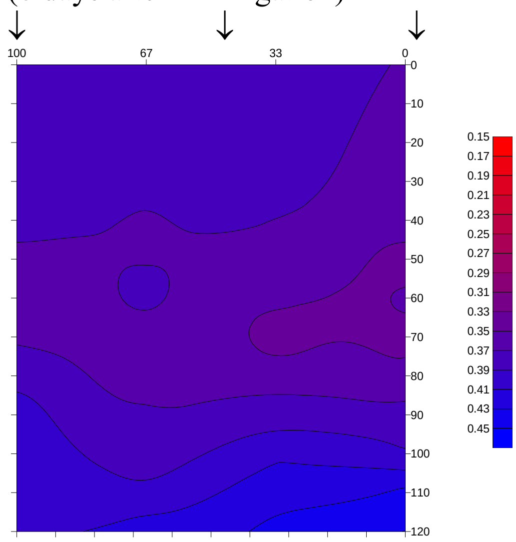
15/2/2004 1606
(2 hr after 3rd irrigation)



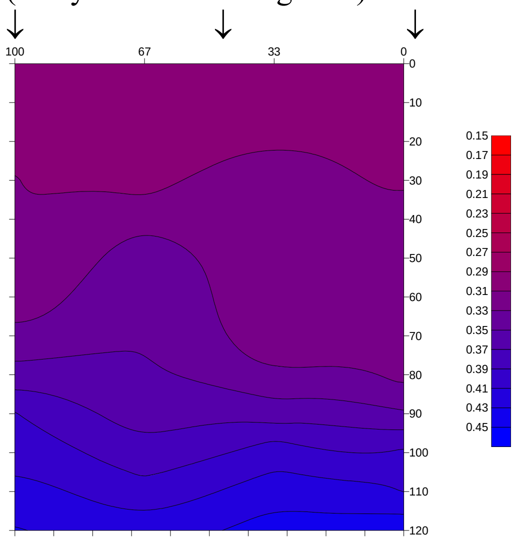
19/2/2004 1630
(2hrs before 4th irrigation)



27/2/2004 1416
(8 days after 4th irrigation)

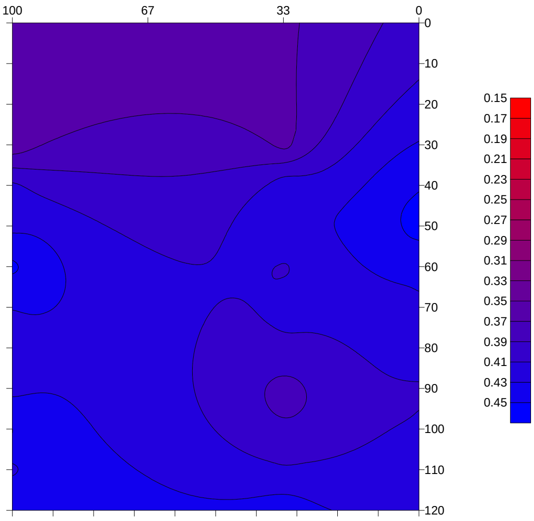


2/3/2004 1416
(2 days before 5th irrigation)

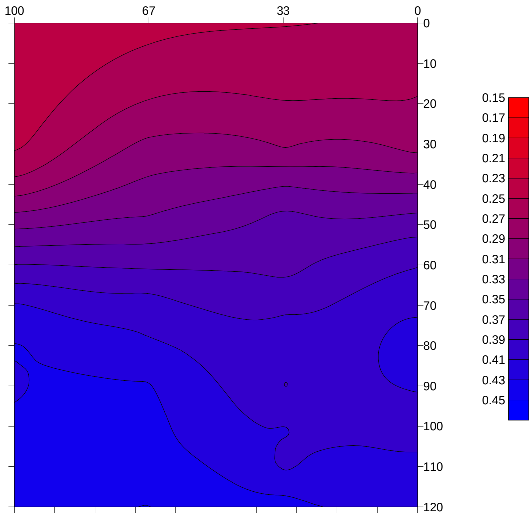


Plot 15 (75% Alt. every)

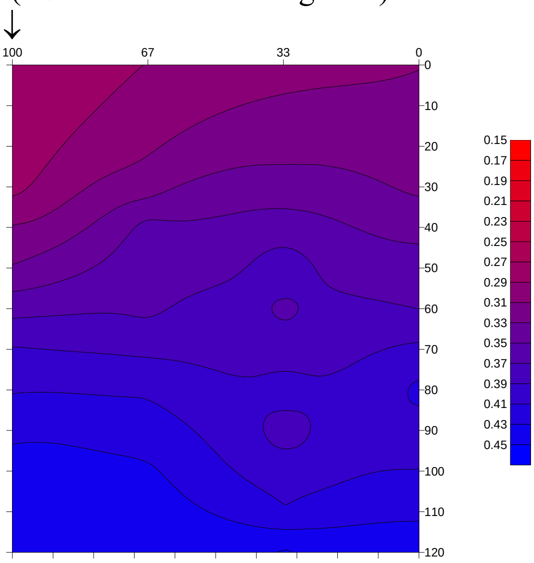
23/12/2003 0000
(7 days before 1st irrigation)



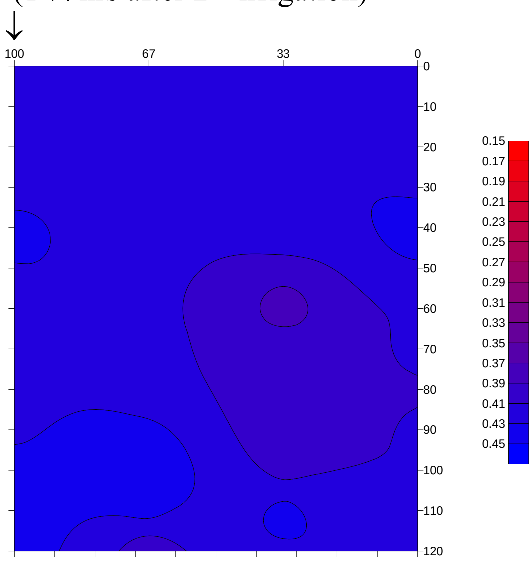
31/12/2003 1758
(6 hours before 1st irrigation)



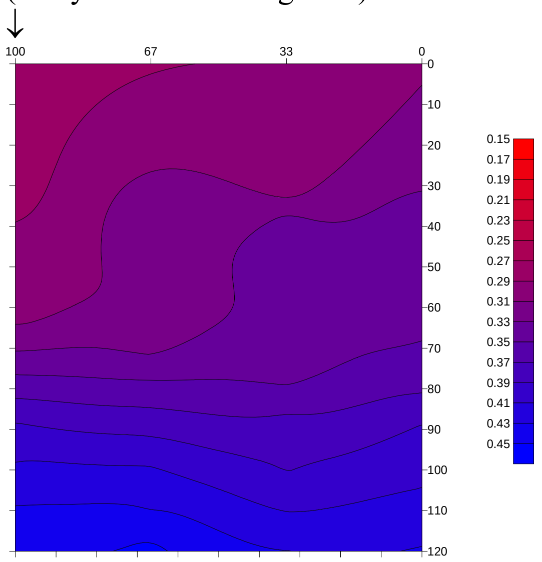
7/1/2004 0545
(1 ¼ hrs before 2nd irrigation)



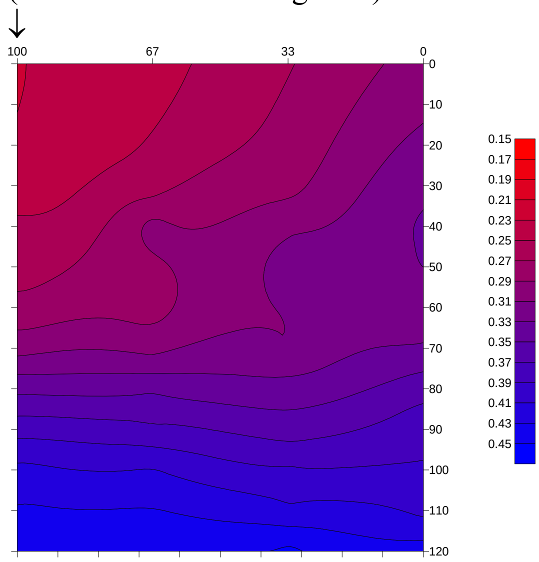
7/1/2004 0815
(1 ¼ hrs after 2nd irrigation)



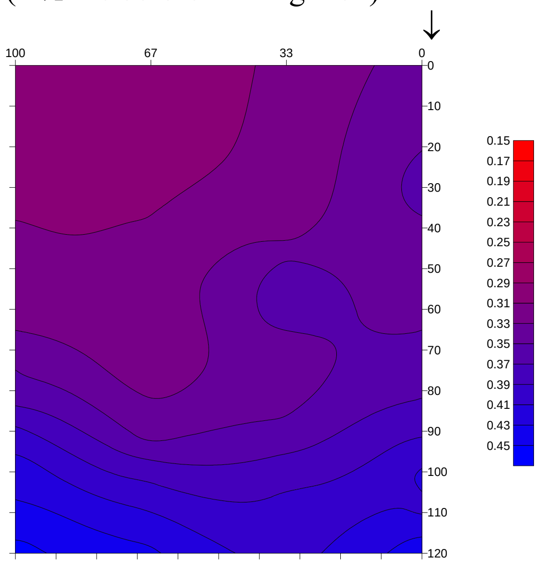
13/2/2004 1617
(2 days before 3rd irrigation)



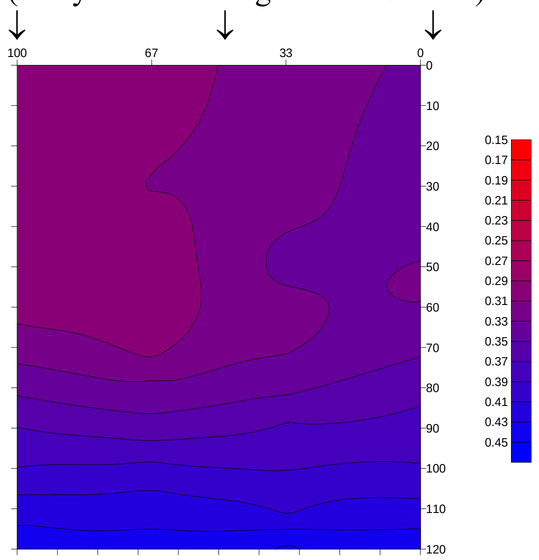
15/2/2004 1745
(2 ¼ hrs before 3rd irrigation)



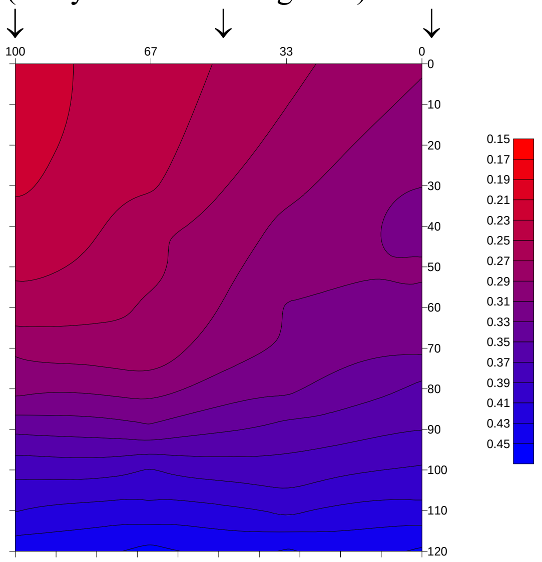
19/2/2004 1723
(6 ½ hrs before 4th irrigation)



27/2/2004 1501
(8 days after 4th irrigation + 17.8mm)

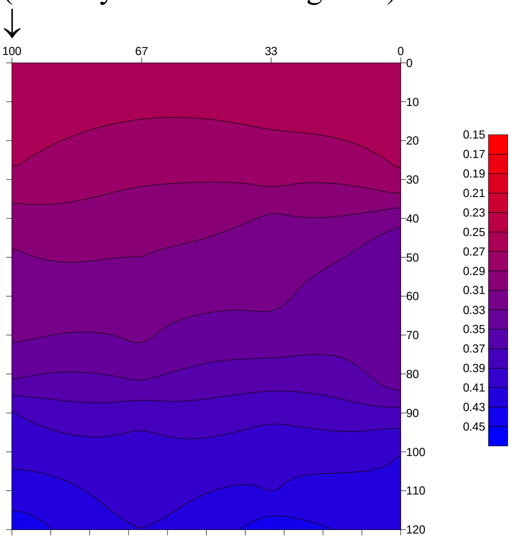


2/3/2004 1519
(2 days before 5th irrigation)

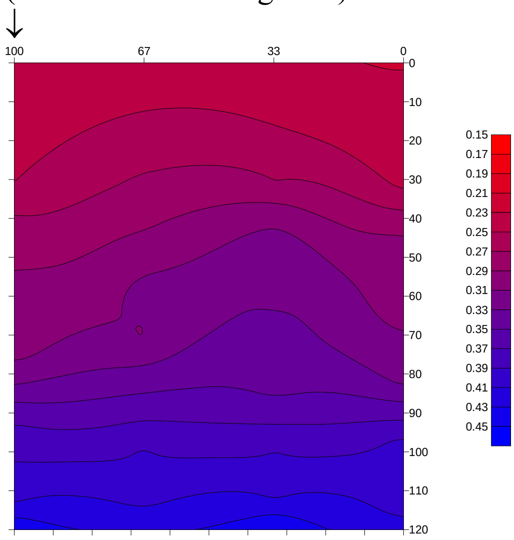


Plot 32 (75% Alt. 2nd)

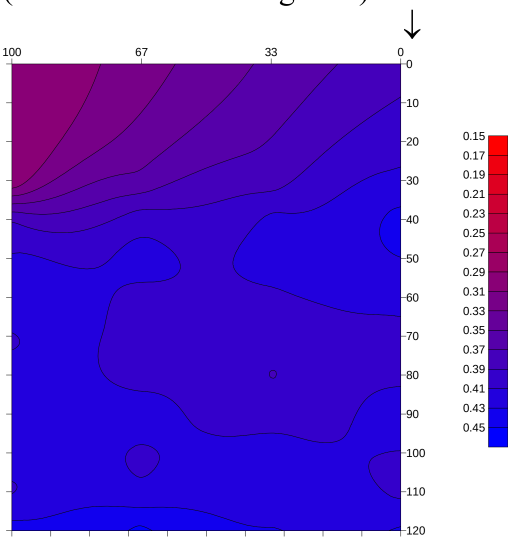
13/2/2004 1818
(2 ½ days before 3rd irrigation)



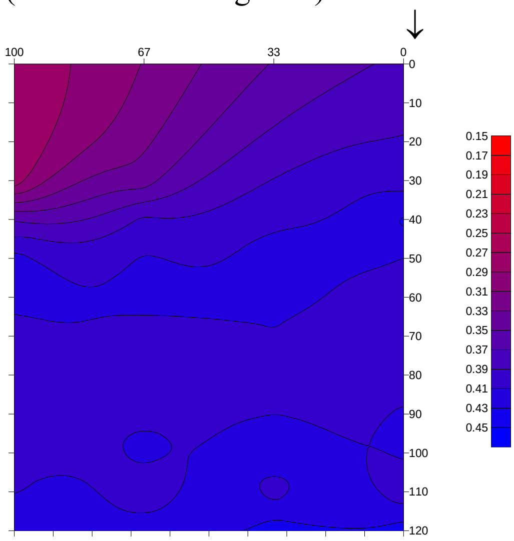
16/2/2004 0640
(2 hrs before 3rd irrigation)



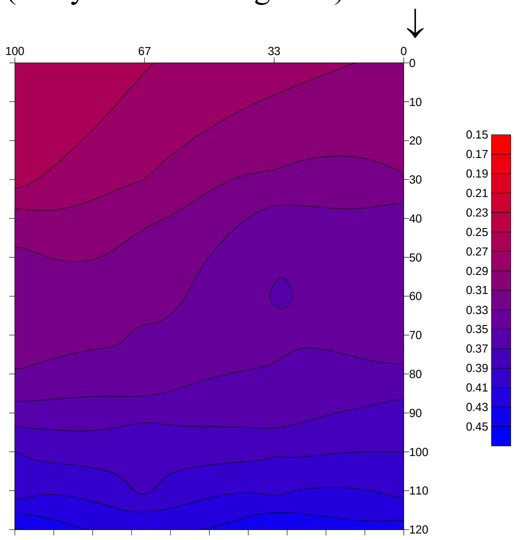
16/2/2004 1027
(2 hrs after the 3rd irrigation)



16/2/2004 1148
(3 hrs after 3rd irrigation)



20/2/2004 1024
(4 days after 3rd irrigation)



Appendix F. Soil, plant and climatic options used for parameterization of Hydrus2D.

Summary of pre-processing information and parameters used in the model for the soil type and field layout investigated is outlined below.

Main processes

- Components of the model required were Water flow and Root-water Uptake

Geometry Information

- Length units were in metres
- Geometry Type, General
- Type of Flow, Vertical Plane
- Soil Profile, 4 Number of Materials, 1 Number of Layers

Time Information

- Time units, set in days
- Time Discretization, Initial and Final time varied with each simulation, Initial time step, Minimum time step and Maximum time step were; 8.64seconds, 0.0864 seconds and 0.1 days respectively
- Boundary Conditions, selected as Time-variable boundary conditions with one time-variable boundary record.

Print Information

- Default, all check boxes selected.

Iteration Criteria

- Iteration Criteria, 50 = maximum number of iterations, water content tolerance and pressure head tolerance both set at 0.001
- Time Step Control, set as default
- Internal Interpolation Tables, set as default.

Soil Parameters

Soil Hydraulic Model

- Hydraulic Model, van Genuchten-Mualem was chosen and 'with air-entry value of -2cm' parameter checked. The use of an air entry value can become particularly important to the hydraulic conductivity function when modelling soil of high clay content (Rassam *et al*, 2003).
- Hysteresis, no hysteresis was selected due to the inability to appropriately parameterise

Plant Parameters

Root Water Uptake Model

- Water Uptake Reduction Model, Feddes was selected

Feddes model assigns plant water uptake at each point in the root zone according to the local pressure head conditions.

- No solute stress model was selected
- Feddes' Parameters, PO, POpt, P2H, P2L, P3, r2H and r2L = -1, -2, -20, -100, -150, 0.008 and 0.003 respectively.

Time Variable Boundary Conditions

- hCritA = 3000, rGWL = 0, GWL = 0.05