Subsurface Drip Irrigated Cotton.

Determination of crop water use and effects on growth and production of different levels of irrigation.

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Certificate of Originality

The text of this thesis contains no material which has been accepted as part of the requirements for any other degree or diploma in any University or any material previously published or written unless due reference to that material is made.

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Abstract

A field experiment on cotton comparing irrigation treatments was conducted at Warren in the 1999/2000 and 2000/2001 seasons. The control was irrigated at 100% of predicted crop water use (ET_{crop}), and three treatments that applied 50%, 75% and 125% ET_{crop}.

Cotton yield was greatest in the 100% treatment followed by the 75% and 125% treatments with lowest yield coming from the 50% treatment for 1999/2000 season. In contrast the 100% and 125% were similar followed by the 75% and 50% for the 2000/2001 season. This yield trend, combined with similar soil moisture contents in both the 100% and 125% treatments, suggests that the 100% treatment was supplying adequate water to satisfy crop demand for the 1999/2000 season. Some water stress was observed in the mid season in 2000/2001 season because of small amounts of under-irrigation (0.5 mm / day).

We found that the irrigation efficiency was limited in both seasons by the large amount of water required to germinate the crop (27% of water applied to the 100% treatment). It is clear that it would be better to use this extra irrigation water to obtain the greater production recorded between the 50% and 100% treatments than to use it only for crop establishment.

We found that gradual development of water stress (by under-irrigating daily) allowed cotton plants to make osmotic adjustments that allowed the 50% treatment to yield only 17% less than the 100% treatment despite only receiving 31% less water.

Neutron probe readings showed that treatments receiving insufficient water to satisfy crop demand were able to extract water from part of the soil profile that was not wet by irrigation. Use of this water allowed the 50% and 75% treatments to grow at similar rates to the 100% and 125% treatments for one month in peak growing conditions after the soil was saturated by rain in late December (1999/2000 season) while rain in November of the 2000/2001 season had a similar effect.

Neutron probe readings proved to be sensitive to small changes in applied water and hence are a useful scheduling tool for drip irrigated cotton.

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1 Introduction

Drip irrigation has been advocated as one way of improving both yield and water use efficiency for irrigated cotton. It has even been claimed that drip irrigation can be used to 'crop areas previously considered unsuitable for conventional irrigation methods'.... because.... 'the root zone is maintained at both optimal water and nutrient levels' (Anon, 1988). In this context drip irrigation may be considered a 'soil independent' irrigation system where the uniformity of application of water and nutrients by the irrigation system overcomes variability in soil properties. Irrigators have been led to believe that the precision of application of water to the crop from drip irrigation will enable soil and climatic limitations to be to be adequately managed.

Performance of drip irrigation systems in Australian cotton has been variable. In a four year field experiment, Constable and Hodgson (1990) recorded a 4% increase in lint yield of cotton irrigated by subsurface drip compared to furrow irrigation. In contrast O'Connell (1998) reported a 33% yield improvement from conversion furrow irrigation of sodic clay to subsurface drip at Lake Tandou (Menindee), However, Hulme (1998) stated that half the area under drip irrigation in the Macquarie Valley in the 1997/98 season yielded less than the valley average. The relatively poor performance of these systems was attributed to suboptimal irrigation management based on observed cotton water deficit stress.

With regards to water Australian cotton growers have claimed that drip irrigation led to significant savings when compared to furrow irrigation. Water savings of 47% have been reported at Emerald in Central Queensland (Anon 1998). Raine *et al.* (2000) reported that 48% of growers achieved 25-50% water savings over furrow irrigation, 33% achieved between 50 and 75% savings and the remaining 19% achieved less than 25% water savings. Large water savings have also been reported overseas with savings of 50% have been reported in Arizona (USA) (Wuertz and Tollefson 1992) and 45% in California (DeTar *et al.*, 1994). These claims have been viewed with scepticism because different methods are used to measure water volumes on and off furrow and drip irrigated fields. However, researchers have found that drip irrigated cotton can have high water use efficiency by making good use of water stored in the soil (Hutchmaker *et al.*, 1994).

A portion of subsurface drip irrigation (SDI) systems installed in Australia have been on hard setting red soil types to overcome early season deep percolation and poor infiltration latter in the season.

Hardsetting soils are those that tend to form a crust after the first irrigation event, reducing the infiltration of water into the profile on subsequent irrigations. Infiltration on the first irrigation is generally exceptionally good because tillage conducted prior has loosened the soil and usually results in deep drainage losses. Subsequent irrigations decline in infiltration to a point where it becomes difficult to supply sufficient water to the crop using surface irrigation. These hardsetting red soils are common in most of the cotton growing areas of Australia, but are not regarded as suitable for irrigation because of management difficulties. However cotton farmers are using these soils because that is the soil type present on their farm. The lack of water logging re-entry access to these fields after rain/irrigation are some of the potential advantages of these soils over heavier clay based soil types commonly used in cotton production.

Due to the relatively poor performance of SDI in Australia (Raine *et al.*, 2000), particularly on hardsetting red soils, appropriate irrigation management guidelines are needed. It is the purpose of this thesis to investigate cotton grown under SDI to better match the crop water use with the application of irrigation water.

A field experiment was established on a subsurface drip irrigated cotton field near Warren to:

1. Determine the effect of a range of irrigation application rates on cotton growth and production.

2. Estimate potential daily crop evapotranspiration (ET_{crop}) of cotton.

2 Literature Review

2.1 Introduction

Subsurface drip irrigation (SDI) has been used for cotton production in Australia for more than 25 years (Raine *et al.*, 2000). During the 1980s, trials were conducted comparing drip and furrow irrigated cotton on cracking grey clays at Narrabri. Researchers found little or no yield response with small water savings (Constable and Hodgson 1990). With none of the systems installed for cotton during that time being operational today. Despite this gloomy start, cotton growers are still installing drip irrigation systems for a variety of reasons;

- to overcome soil problems (such as hardsetting surface and sodic subsoils)
- reduce effects of water logging
- enhance accessibility for ground spraying and tillage equipment
- save water
- yield increases

A portion of these recent SDI installations are on hard setting red soils to overcome early season deep percolation and poor infiltration latter in the season (Hulme and Obrien 2000a). However drip irrigated cotton has failed to deliver the increase in yields needed to make the installations economically viable. A possible reason for this has been identified as poor irrigation management, with crops being either under-irrigated or over-irrigated, or both.

To understand the basis of an appropriate drip irrigation system for this environment, and its best management, the literature review will look at the nature of hard setting red soils as well as the movement and measurement of water in the soil. The influence of water supplies on cotton plant shoot and root development and the effects of deficit irrigation on cotton will also be reviewed.

2.2 Water and soil relations under Subsurface Drip Irrigation

2.2.1. Hardsetting Red Soils.

In Australia, approximately 13% of the total land area is covered by soils that are prone to hardsetting (Mullins *et al.*, 1990). With the exception of the Lake Tandou area, all cotton growing areas in Australia contain soils that are prone to set hard (Northcote *et al.*, 1975) with hardsetting soils being the second most commonly used soil for cotton irrigation after cracking clays.. In the Macquarie Valley irrigation area of NSW, some 35% of cotton production was located on soils that are prone to be hardsetting (Elliott 1995).

Hardsetting typically occurs in soils with low amounts of organic matter, high proportions of fine sand and silt and little swelling clay (Mullins *et al.*, 1990; Hulme and Elliot, 1995). Mullins *et al.* (1990) claimed that a soils potential to set hard was partly determined by its texture and mineralogy. He also gave a graphical image of the range of soil types that are potentially hardsetting (Figure 2.1). The combination of these properties causes hardsetting soils to have an unstable structure on wetting (Hall *et al.*, 1994a) and subsequently, to set to a hard, structureless mass during drying.

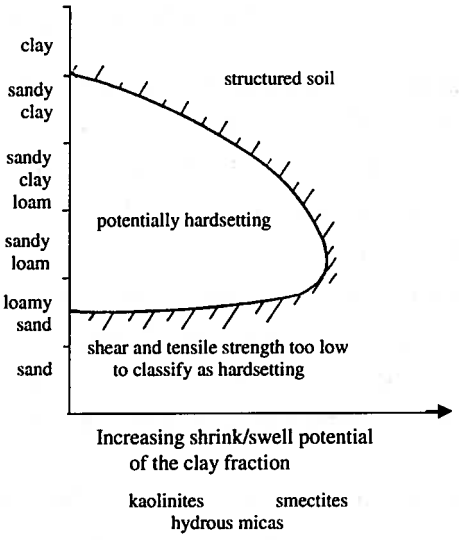


Figure 2.1. The range of soil textures in which hardsetting is likely to be encountered in relation to clay mineralogy. (silty soils can also be hardsetting and would be placed somewhere in the middle of this range.) Source: Mullins *et al.* (1990)

Mullins *et al.* (1990) describe hardsetting as a two or possibly three stage process (Figure 2.2): slumping, shrinkage and development of soil strength.

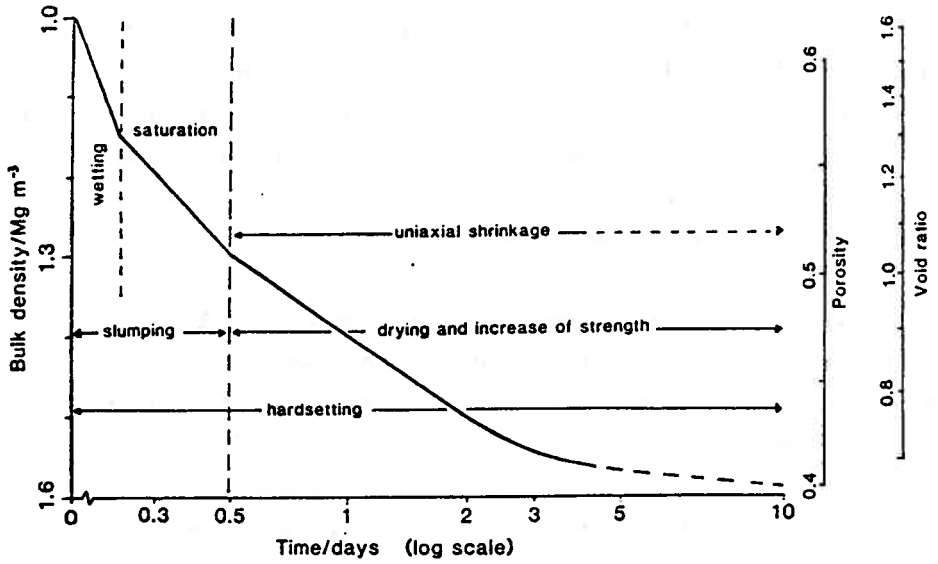


Figure 2.2. Hypothetical diagram to show the sequence of possible compaction processes that operating during hardsetting of an initially aggregated layer of soil at 0.1 m depth. Source: Mullins *et al.* (1990)

Slumping is defined by Mullins *et al.* (1990) as the process that predisposes the soil so that it sets hard upon drying. During the process, soil aggregates will both soften and swell simultaneously during wetting. The energy released can cause slaking, resulting in the suspension of silt and clay microaggregrates. Slaking is defined by Anderson *et al.* (1999) as the... "collapse of aggregates in water to form microaggregrates, due to the breakage of bonds formed, for example, by organic matter." The aggregates disintegrate because they have insufficient strength to withstand the stresses associated with rapid water uptake, such as those caused by rapid release of heat of wetting, compression of trapped air, mechanical action of rapidly moving water or by differential swelling (Mullins *et al.*, 1990).

Shrinkage is the second stage of hardsetting and is described by Mullins *et al.* (1990) as the realignment of the remnants of the disrupted aggregates within the fabric of the soil. Shrinkage is of importance because the close proximity of soil particles may contribute to an increase in soil strength.

The final stage of hardsetting is the development of soil strength occurs as the soil dries. A large component of the strength occurs as small soil particles suspended in solution are

deposited on the surface of larger particles. The annular bonds formed during this process are large contributors to soil strength, with a lessor contributor being the effect of matric potential as the soil particles can remain in suspension even to a relatively low water potentials (Mullins *et al.*, 1990).

Hardsetting of the soil can result in poor seedling emergence, root growth and slow water penetration (Cockcroft and Martin, 1981; Mullins *et al.*, 1990). These properties often limit the yield potential of these soils for irrigated agriculture.

2.2.2. Amelioration of Hardsetting Red Soil

There have been numerous attempts to ameliorate hard setting soils to reduce hardsetting characteristics such as crusting, slaking, and slumping. Hall *et al.* (1994 a,b,c) trialled deep mouldboard ploughing, gypsum application and double cropping in a range of combinations. The results showed that the treatments were only effective in the short term, but if repeated could give longer-term benefits. Willis *et al.* (1999), in a similar trial, observed the effects of tillage and irrigation method. It was found that water entry into hardsetting soils could be improved by double cropping and stubble retention, mainly as a result of reducing soil strength. Deep tillage combined with permanent beds, however, did not improve yield possibly because of the compaction effects of mouldboard ploughing. The results of these experiments are consistent to those of Sinclair *et al.* (1992) who looked at the effects of cultivations and mulch on water infiltration and found that, initially, infiltration improved but declined over time.

Table 2.1. Summary of amelioration experiments and trials on hardsetting soil types.

	Amelioration method	Increased water infiltration	Improved soil properties	Length of effect
Hall *et al.* (1994abc)	Ploughing	yes		1 season
	Gypsum	yes		~2 seasons
	Double cropping	yes		~2 seasons
Willis *et al.* (1999)	Tillage	no		
	Irrigation layout	no		
	Crop rotation	yes		
Sinclair *et al.* (1992)	Cultivation	yes		Declined through season
	Calcium addition	no		
	Added mulch	yes		Declined through season
	Sown oat mulch	yes		Declined through season
Tisdall *et al.* (1978)	Microbial activity		yes	< 1 season
Hulugalle *et al.* (2000)	Drip irrigation		Improved soil physical but not chemical properties	

Tisdall *et al.* (1978) examined the effect of microbial activity on soil stability, finding that microbial activity can compensate for some of the bonds broken by physical disruption. In these studied it was also found that the addition of organic material to the soil reduced the prevalence of slaking in the soil. However these benefits were only short lived (less than 32 weeks) and were reduced further by cultivation.

It has been suggested that drip irrigation can be used to overcome the problems associated with hardsetting red soils (Bannister 1988; Anon 1988). Raine *et al.* (2000) reported that 24% of cotton growers using drip irrigation in Australia, installed their systems to overcome hardsetting problems. Hulme and OBrien (2000b) found that water can be successfully introduced to the soil with drip irrigation, thus overcoming the limitations of reduced infiltration through the season.

Hulugalle *et al.* (2000) reported on the differences between furrow and drip irrigated soil properties over a growing season. They found that under both systems, soil physical qualities improved over the season due to decreases in the dispersion and hardsetting indices. However they also found that soil chemical quality declined under both systems due to a decrease in soil fertility indices. Soil pH declined with furrow but not drip irrigation, while organic carbon declined under drip but not furrow. They found that the replacement of furrow irrigation with drip irrigation on heavier textured loamy soils can result in short term

soil improvements, however these improvements were not evident on lighter textured soil types (Hulugalle *et al.*, 2001). Hall 1994b also found improvements in infiltration rate and moisture holding capacities as a result of using drip, but the improvements proved not to be permanent and only lasted for short periods (less than two years). Hall (1994b) concluded; "despite substantial improvements after 2 years in some treatments, soil hydraulic properties were inadequate for optimal irrigated cropping." Subsurface drip irrigation overcame poor infiltration but did not necessarily improve soil structure.

2.2.3. Water Movement

Soil water behaves in a similar way to all fluids, it will move from an area of low energy potential to an area of high energy potential and equalize its energy status in its surroundings. It is the difference in the energy state of the water at each point that is the basis of the soil's water potential (Hanks and Ashcroft 1980; Hillel, 1971). Water in the soil moves according to gravitational and capillary forces (Craze and Hamilton, 1991). Water movement by capillary flow is the result of differences in soil matric potential. All soil water is under the influence of gravity (Hillel, 1971) which will affect soil water movement, especially when the soil is close to saturated.

The infiltration and water holding characteristics of soils are dependent on the size, number of soil pores and distribution of soil pores, which is closely linked to texture, and to a lesser extent soil structure and structural stability (Craze and Hamilton, 1991).

The infiltration rate of a soil is a measure of the rate at the maximum rate of water penetration through the soil surface. Therefore, when the application rate of water via irrigation is less than the soil infiltration rate, water will penetrate through the soil surface equal to the application rate. However, when the water supply exceeds infiltration rate, then the infiltration rate determines the flux of water into the soil and water in excess is either ponded on the surface or becomes runoff.

Infiltration normally declines from the initial wetting to the point where the soil approaches saturation (Hillel, 1971). Infiltration rate also depends on the initial wetness as well as texture, structure and uniformity of the soil. Localised surface conditions can also affect infiltration with a thin surface crust reducing the rate of water entry into the soil.

Closely linked to the infiltration rate of the soil is the hydraulic conductivity, which is a measure of the rate of water transport through the soil under the influence of gravity.

The hydraulic conductivity of irrigated hardsetting soils is highly variable. In research done in the Macquarie Valley Bird *et al.* (1996) reported values in the range of 20 – 100 mm per day while Willis and Hulme (1996) reported that red brown earths have a saturated hydraulic conductivity ranging from 0.6 to 296 mm per day (mean of 32 mm per day). McKenzie (1992) also reported a similar large range in estimates of annual drainage of 0-300 mm in the Macquarie Valley.

As with hydraulic conductivity, there is a wide scatter of textures of red brown earths that results in a large variation of available water holding capacities in the range of 120 to 240 mm m^{-1} (Greacen, 1981). This wide range of values is reflected by McKenzie's (1992) studies of the soil types in the Macquarie Valley (where hard setting soil types are common), with a range of available water capacities (AWC), for non-cracking clays ranging from less than 0.1 to greater than 0.3 mm mm^{-1} (Figure 2.3). This variation occurred within as well as between soil types. For example the Byron soil type (Figure 2.3) had AWC from 0.08 to 0.25 mm mm^{-1}. This variation is commonly observed in commercial cotton fields.

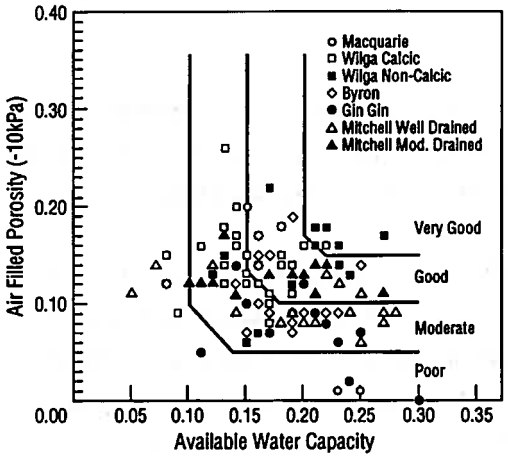


Figure 2.3. Structural quality at 0.10 m for all non-cracking clays in the Macquarie Valley. Source: McKenzie (1992)

Water content of hardsetting soils can be limited by its hardsetting nature. Cockroft and Martin (1981) state that total water intake of hardsetting red soils during (flood) irrigation rarely exceeds 50 mm due to the poor physical properties of the topsoil. Hence the available water content in the root zone is likely to be lower than the maximum values of 150-200mm calculated by Greacen (1981) and McKenzie (1992). Poor infiltration combined with impeded root development (Cockcroft and Martin, 1981; Mullins *et al.*, 1990; Hall *et al.*,

1994a) has the potential to reduce the irrigation interval (time between irrigation events) to less than 10 days (Hall *et al.*, 1994b). Local experience in the Macquarie Valley (John O'Brien, personal communication) is that irrigation intervals are reduced to 6-7 day cycles during peak crop water requirement on hardsetting red soils.

Due to the hardsetting nature and poor infiltration, cultivation is carried out in order to loosen the ground to establish crops (Mullins *et al.*, 1990). The result is often that, due to the degradation of soil structure (due to cultivation), a subsequent irrigation or rainfall event can cause slumping (see section 2.2.1). In the extreme, Cockroft and Martin (1981) state that continuing cultivation will deteriorate soil structure to an extent whereby hardsetting becomes chronic and that after three years "..worthwhile crops are impossible to grow."

After cultivation or soil disturbance, hardsetting red soils have a high permeability on the first wetting event and subsequent water events decrease in infiltration (Hulme and OBrien, 2000a: Sinclair *et al.*, 1992). Similarly, Willis *et al* (1997) reported on two soil types (red-brown earth and cracking grey clay), both had the highest deep percolation on the first irrigation. This can be attributed to the cultivation having a loosening effect on the soil, allowing increased infiltration. However the red soil type showed less irrigation water entered the soil in subsequent irrigations as a result of soil structure degradation following an irrigation event (slumping, slaking and shrinkage).

As the hardsetting properties are usually limited to the topsoil, particularly if it has been disturbed, then the undisturbed subsoil can retain good structure hence promoting drainage while not deterring root growth (Mullins *et al.*, 1990). This is of consequence for sub surface drip irrigation as water is delivered to the soil at a point on a vertical transect between disturbed surface soil and undisturbed subsurface soils.

As well as differing with regards to point of water application, drip irrigation can also introduce water to the soil under pressure. If the soil cannot transfer the water away from the drip emitter at least as fast as it is being applied then there will be an increase in the water pressure immediately surrounding the emitter. Battam and Sutton (2000) found that this can cause water surfacing and can affect the output from the emitters due to the reduction in the potential gradient across the emitter (between the inside and the outside of the drip tape). Applying water too rapidly to the soil with SDI can increase the variation of application rate across the field (Shani *et al.*, 1996). Battam and Sutton (2000) estimated the intake rate of a hardsetting soil type to be around 0.3-0.6 litres per hour per emitter at shallower depths (less than 30 cm).

Creighton *et al.* (1999) stated that "...a drip irrigation system should be designed so that the rate at which you apply water does not exceed the soils infiltration rate" as faster application will lead to a greater degree of saturation and hence predominantly downward flow, possibly generating water losses beneath the root zone.

2.2.4. Plant Available Water Capacity of Hardsetting Red Soil with Drip Irrigation.

In order to determine the total plant available water capacity (PAWC) of a field under drip irrigation the following must be known:

- Rootzone location
- Soil texture (field capacity and wilting point) hence AWC of the soil
- Saturated hydraulic conductivity
- Wetted soil volume
- Lateral and dripper spacing

PAWC was defined by Anderson *et al.* (1999) as "the maximum amount of water that a soil can hold and later release to plant roots. Water held between field capacity and permanent wilting point is regarded as being available to plants". Readily available water (RAW) is defined as being the proportion of total available water which can be easily or readily used by plants before signs of moisture stress and reduced growth appear (Anderson *et al.*, 1999). As mentioned in section 2.2.3, there is a wide range in available water holding capacities (120-240 mm m^{-1}) and saturated hydraulic conductivities (0.6 to 296 mm per day, mean: 32 mm day^{-1}) of hardsetting soil types. It could be then assumed that there is an equally wide range of values of PAWC.

For red soils this is commonly the case as cotton drip systems are specified to provide 1-2 mm/hr (because of limited lateral movement this amount tends to be spatially concentrated). While this is less than the infiltration rates reported by Willis and Hulme (1996) of 5-140 mm/hr, it must be remembered that the water is being applied from a point source. A point source has the effect of concentrating the water in a small area inducing soil saturation (see Figure 2.4). If the vertical flow is greater than the lateral flow, there is the potential for deep drainage losses.

Battam *et al.* (2000a) mapped the actual wetting front of a hardsetting red soil by simulating drip irrigation with a point source emitter (Figure 2.4), giving a measure of the wetted area.

The soil had a maximum lateral water spread of 70 cm (35 cm each side of the source) and reached a depth of 90cm after 12 hours. Hence the lateral spacing is crucial to determining the wetted volume of the soil under drip irrigation, with closer lateral spacings resulting in a higher proportion of soil being wet by the SDI system.

Battam *et al.* (2000a) observed the wetting front in a hardsetting red soil (which was dry prior to the irrigation event) had reached a depth of 90 cm after 12 hours at 1.2 mm/hr application. He then concluded that if this is the bottom of the effective root zone then the maximum application period should be limited to 12 hour shifts.

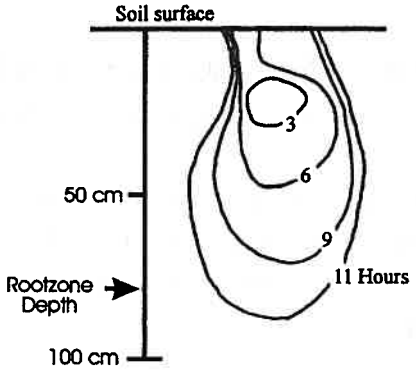


Figure 2.4. Changes in the wetted front position around a point source drip emitter. Source: Battam *et al* (2000a)

For drip irrigated cotton, the recommendation for lateral spacing has traditionally been 2 metres (T Tape, 1996) because it fits into the current crop configuration and is most economical in relation to installation and product costs (Schoneman *et al.*, 1992). Due to promotion of drip irrigation as a soil independent system and economic considerations, this spacing has been recommended and implemented with little or no regard to soil properties. As such, approximately 81% of drip irrigation installations on Australian cotton are on 2 metre spacing (Raine *et al.*, 2000). However Hulme and OBrien, (2000a) found that the restriction of lateral water movement in hardsetting red soils constrains management and lateral spacings should be determined based on site specific soil properties. Battam *et al.* (2000b) confirmed this with a number of soil surveys that revealed different wetting patterns for different soil types and hence recommended different lateral spacings dependent on site specific soil properties.

Furthermore, Moreshet *et al.* (1996) concluded that drippers laid at two metre spacing expose cotton to frequent short periods of water stress due to a lowering of the soil water potential

near the roots. They found that during the wetted cycle, a sufficient number of roots lost contact with the wet soil lowering the effective plant hydraulic conductance. However it must be noted that this experiment was not irrigated daily; irrigation intervals ranged from 2 – 14 days. A system that is operated daily or more often will have smaller fluctuations in the size of the wetted area, and may also have a smaller wetted area.

The PAWC of a red soil under SDI is going to be a function of the soil properties (field capacity and permanent wilting point) and the area wetted by the irrigation system. The wetted area of a drip irrigation system will be a function of the time it is running, the saturated hydraulic conductivity of the soil and lateral and emitter spacing.

2.2.5. Measurement of Water Movement in Drip Irrigated Soil

Water use efficiency, if you don't measure it you can't manage it! (Hearn *et al.*, 1997)

In order to measure rootzone soil moisture status there are a number of methods for measuring soil moisture status. Charlesworth, (2000) lists 24 different soil moisture monitoring devices (see Appendix 1).that fall into 2 categories, those that measure soil water potential and those that estimate volumetric water content

In the Australian cotton industry the main methods used are neutron moderation method (NMM) (Anon, 2000) and frequency domain reflectometry (FDR) and, to a lesser degree, porous media type instruments. The NMM has been applied as a tool in Australia by Cull *et al* (1981a,b). The development and adoption of this technology was widespread and its use in the industry is still dominant, however the use of the NMM is not common on hardsetting soils because of poor infiltration (Willis *et al.*, 1997; Hulme and OBrien 2000a). Raine *et al.* (2000) reported that 57% of drip irrigators in the Australian cotton industry used a combination of soil measurements as well as other tools to schedule irrigations, while 13 and 17% relied entirely on neutron moderation and FDR respectively.

The limitation with drip irrigation, especially subsurface, is the location of the sensor in relation to the wetted area. Hulme and OBrien (2000a) demonstrated that the NMM access tubes 50 cm from the water source did not detect water applied in drip irrigation whereas access tubes located 10 cm from the irrigation source did. Dearden (2000) found similar problems in grapevines when sensors were placed within or on the edge of wetted zones as both locations gave different readings for the same input of water. Muldoon *et al.* (2000) monitored the water extraction of rockmelons 10, 20 and 30 cm away from the drip tape and

observed extraction declined with distance from the tape indicating a limited wetted area and extraction zone.

NMM and other systems (Diviner®) that require manual readings to be taken are limited in measuring water movement in the soil under a drip system as the readings are generally taken daily or less frequently. Problems can occur in that the changes in soil moisture are small and may be occurring daily or twice daily depending on the scheduling program. Henggeler (1999) found that "one of the major advantages of Enviroscan® (FDR) compared to the Probe (NMM) is that it takes a moisture reading up to every minute. Despite this observation Hulme and OBrien (2000b) found that NMM tubes placed next to an SDI emitter were sensitive to irrigation.

Clearly there are limitations associated with monitoring soil moisture around a point source emitter that can result in misleading data (Dearden 2000; Coelho and Or 1996).

It therefore could be concluded that soil moisture sensing requires human input and some check is needed to ensure that:

- Water is infiltrating to the sensors (dig a hole to check)
- Monitoring equipment is adequately covering the entire root zone
- Sensors sited in representative areas

2.3 Water and plant relations

2.3.1. Root Growth and Water Uptake

The cotton plant has a taproot system with many laterals. First formed cotton roots will generally grow vertically down, if they are not impeded and depending on soil conditions, they can grow from 50-90 mm per day (Hearn, 1979). However growth rate is reduced dramatically (~8 mm per day) by cool conditions.

Cotton seedlings can suffer from cold shock if the minimum daily temperature drops below 11°C (Allen *et al.*, 1998) and can become susceptible to root diseases such as rhizoctonia and black root rot which will further inhibit root growth and shoot development.

Cotton roots have been known to grow to 3 m depth (Hearn, 1979) and can reach a maximum density of 1.6 cm/cm^3 in the top 15 cm of soil (Schwab *et al.*, 2000). However root distribution is highly variable and will depend on soil condition and, to some extent, plant variety. Maximum rooting depth has been reported to occur 117 days after planting and dry matter production continued to increase until 128 days after planting (Mullins *et al.*, 1997). Radin *et al.* (1989) found that root mass can start to deteriorate under a heavy fruit load and this trend is slow to be reversed. Cotton follows a similar root distribution to other field crops as shown in Table 2.2.

Table 2.2. General root distribution in relation to depth. (Plaut *et al.*, 1996).

Percentage of roots	Depth (cm)
40-50	0-30
30-35	30-60
~25	>60

Meyer and Ritchie (1980) showed that cotton could absorb water from 120 cm without any effect on leaf area, leaf water potential or rate of water uptake when compared with shallow rooted plants. It has been shown that the amount of water stored in the soil can influence the rooting depth (Hearn, 1979), with greater volumes of stored soil water generally resulted in deeper rooting depth. Hearn (1979) found that water shortage could increase root growth and root exploration of the soil. He also found that increasing the stored water in the soil from 150 to 450 mm increased the rooting depth of cotton from 1 m to 2 m. However Plaut *et al.* (1996) found that hydrotropism (root growth through dry soil to moisture) in cotton was not apparent.

Soil conditions that will effect root growth are strength, hydraulic conductivity, soil water potential and the presence of wetter soil in the root range (Taylor and Klepper, 1974). Soil

strength can inhibit and in extreme cases prohibit root growth (Grimes *et al.*, 1972; Mullins *et al.*, 1990). However cotton roots are capable of penetrating layers of high soil strength (compacted layer) although water extraction below this region was reduced. (Hulme *et al.*, 1991; Stirzaker *et al.*, 1996)

Taylor and Klepper (1974) were unable to separate the effects on roots of hydraulic conductivity, soil water potential, soil strength and the presence of wetter soil in the profile. However, Taylor and Klepper (1974) found that cotton roots will grow in drying soils until water content declines to 6–7% (-0.1 MPa potential). Observations of root distribution under drip irrigation would indicate that roots will become concentrated in wetter parts of the profile. (Borthwick, 2000; Carmi *et al.*, 1992).

Passioura and Stirzaker (1993) found that roots sense 'difficult' soil conditions (drier or harder) and send inhibitory signals to leaves to slow expansion and close stomata before a fall in shoot water status or the supply of water is affected. Plants respond to these feed forward signals in anticipation of future adverse conditions. These signals were found to override the water status of the shoot and are possibly hormonal.

Drip Irrigation and Root Growth

Subsurface drip irrigation wets the soil in a different pattern when compared to other forms of irrigation such as flood or sprinkler. This can have implications for the roots. If the wetted area doesn't extend to the seed then there must be sufficient initial root growth to reach the wetted soil volume (Plaut *et al.*, 1996). As cotton is not necessarily hydrotropic (Plaut *et al.*, 1996), the soil through which the roots are growing must be moist (Taylor and Klepper, 1974).

Daily drip irrigation can concentrate cotton roots under the drip emitter (Carmi *et al.*, 1992; Borthwick, 2000). Carmi *et al.* (1992) found that this type of irrigation led to a shortening of the tap root and a tendency for it to grow toward the water source. It was also found that fine roots developed in other parts of the soil (not wet by irrigation) will disappear when the soil water content drops below wilting point. Cotton plants grown with daily drip irrigation developed a high percentage (>90%) of roots less than 1 mm in diameter, thus increasing the root surface area. Carmi *et al.* (1992) hypothesised that the reduction in root size under drip irrigation would lead to a reduction in root carbohydrate demand.

2.3.2. Influence of Water Supply on Cotton Growth and Development

Cotton is an indeterminate plant as it never terminates in a flower. The main-stem will produce a new node every two to three days, fruiting branches start to occur between the fifth and eighth node and fruiting sites occur at regular intervals along the fruiting branch. Node and flower bud (square) production will continue as long as conditions are favourable (Hearn, 1979). Competition for carbohydrates and nutrients increases as the plant grows and ultimately limits the number of fruit the plant can carry. As competition increases, the maturing fruit has priority over small fruit / squares, potentially causing some shedding (loss) of these structures. Hence when the sink limit is reached, square production ceases (Hearn, 1994).

A decrease in applied water can result in a reduction in plant height, reduction in main-stem nodes, leaf area and total dry matter (Hutchmaker *et al.* 1994). The more specific adaptive responses of cotton to changes in moisture status are represented in Figure 2.5.

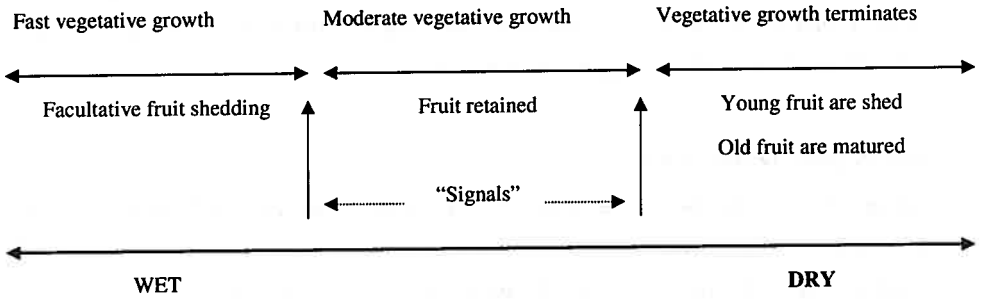


Figure 2.5. Specific adaptive responses of cotton to the environmental water regime. Source: Hearn (1994)

2.3.3. Factors Affecting Evapotranspiration

Evaporation is defined as "the process whereby liquid water is converted into vapour and removed from the evaporating surface. Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation." Transpiration is defined as "consisting of the vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere" and evapotranspiration (ET) is the combination of both (Allen *et al.*, 1998)

The factors that affect ET are weather parameters, crop characteristics, management and environmental factors. At present the FAO modified Penman-Monteith equation is used as the standard method for calculating ET. For a detailed description refer to Allen *et al.* (1998). From the measured weather parameters crop water use can then be calculated. As

of 1998, the sole standard method for determination of crop water use is the FAO Penman-Monteith (Allen *et al.*, 1998).

The relationship between evapotranspiration and cotton production is represented in Figure 2.6. As the water available to the plant declines, so to does the plant evapotranspiration. Therefore it is not surprising to find that like many other crops cotton yield is closely linked to ET. This representation (Figure 2.6) is only for one season's data and may not be applicable to all regions.

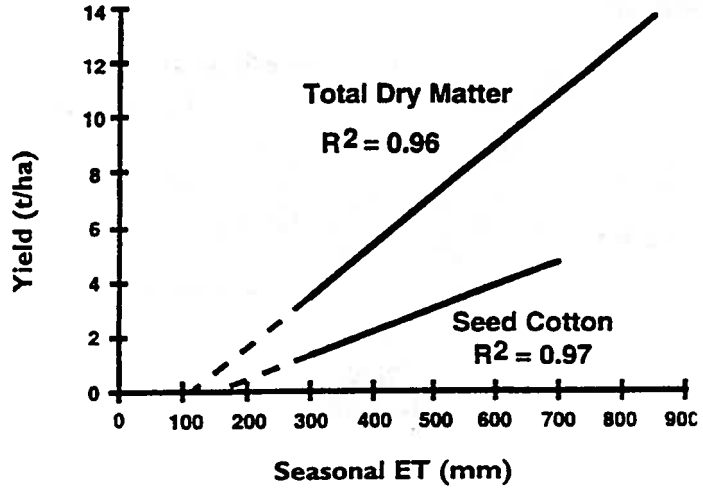


Figure 2.6. Cotton yields as a function of evapotranspiration. Source: Hearn (1994)

Hearn (2000) identified one of the problems in estimating evapotranspiration is the adaptation of the equation to local conditions. In particular the aerodynamic component of the Penman equation. da Roza *et al.* (198?) found that earlier Penman combination equations would derive values (of the aerodynamic component) that varied an average of 158% between two seasons. On the other hand Abdelhadi *et al* (2000) found that the Penman-Monteith equation could be used to estimate crop water use in the Sudan Gezira area with good accuracy. Clearly, site specific validation of the Penman-Monteith model are needed to determine their accuracy before they are used in scheduling irrigations.

In Australia models such as SIRATAC, Ozcot have been developed but are not widely used because of expense in conducting local calibrations and the good performance of the neutron moisture meter in scheduling irrigations.

2.3.4. Measurement of Water Status in Cotton Plants

Just as there is a water balance, there is an energy balance for crops (Figure 2.7) where the inputs must equal the outputs. If one of the components of the balance is changed, then this will have an effect on all other components. For instance, during the day time the sun. If the plant had no mechanism to dissipate the energy, then it would overheat (Hearn, 2000). One of the mechanisms the plant uses to keep cool is evapotranspiration (ET).

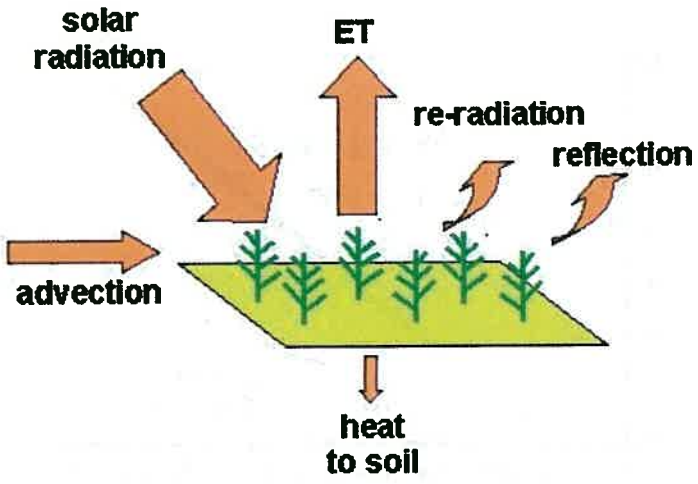


Figure 2.7 Energy balance of a crop. Where solar radiation + advection = ET + re-radiation + reflection. Source: Hearn (2000).

To satisfy its evaporative demand the plant requires water which it usually obtains from the soil surrounding its roots. The mechanism by which the water moves from the soil and through the plant is along gradients in energy potential of the water. Lange *et al.* (1976) define "water potential" as the relative chemical potential of the system concerned per partial molal volume of water. Fundamentally it is the difference in energy between pure free water and water at another point, i.e.: in the soil. Water will move through the soil to the roots under the influence of "soil water potential" (ψ^{soil}) and subsequently through the plant via "leaf water potential" (ψ^{leaf}) (Lange *et al.*, 1976). The water potential of these systems will be influenced by compounds dissolved in the water (osmotic potential), bonds formed with soil particles (matric potential) or plant cell walls, hydrostatic pressure and gravity. The plants water potential is negative and typically lower than that of the surrounding soil, allowing roots to 'suck' water from the soil (Figure 2.8). However, as the soil dries the water potential decreases, making it more difficult for the plant to draw water from the soil. As the

soil dries the rate of water uptake decreases as does the plant water potential and hence ET rate. As a result the leaf temperature rises. Therefore the measure of any of these components can be used to assess crop moisture status.

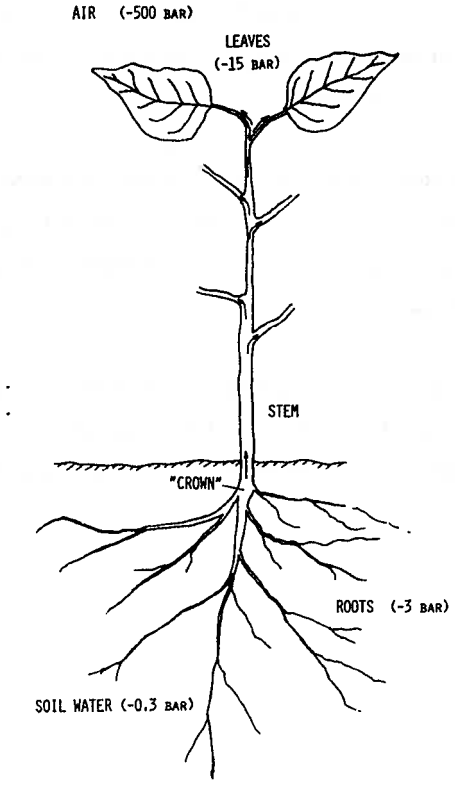


Figure 2.8 Schematic illustration of the variation of water potential along the transpiration stream. Source: Hillel (1980).

The measurement of leaf water potential can be achieved with the pressure chamber method (Scholander *et al.*, 1965) which is a common tool in the cotton industry and is frequently used to schedule the first irrigation. Meron *et al.* (1987) outlined the limitations of this tool, namely diurnal variability, time between leaf cut and measurement and the relatively small number of samples that can be measured. They then set down procedures to reduce the error associated with these measurement techniques which involved holding the leaf in an open aluminium foil sheet, sealing the leaf on cutting, storage of the leaves in a dark, airtight, humid box at room temperature and pressurization of the leaf while still in the wrapping.

The leaf water potential will vary according to the atmospheric demand and the supply of moisture from the soil. Maximum photosynthesis and leaf growth have been reported to occur at potentials above –1.4 MPa (Anon. 1996), with optimum growth rate typically occurring between –1.6 to –1.7 MPa,. However excessive growth may not necessarily be desirable. Leaf growth declines and ceases between –1.8 and –2.4 MPa. Similarly Hearn and Constable (1984) determined that the most agronomically desirable leaf water potential for cotton was between –1.5 to –2.0 MPa.

An indirect method of measuring plant water status is through leaf temperature, which rises when water is limited. The optimum canopy temperature range for cotton growth is between 25 and 31^{O}C (Wanjura and Mahan, 1994). It is within this range that plant metabolism via enzyme activity is maximised.

An even more indirect method of assessing plant moisture status is through the measurement of plant growth such as: height, node length, number of nodes etc. A reduction in plant growth may be due to a water deficit, however other factors such as nutrition can also influence plant growth.

2.4 Deficit irrigation and cotton yield

2.4.1. Physiological Responses of Cotton to Water Deficit Stress.

The product of cotton cultivation is the cotton fibre, which primarily consist of carbohydrate. Limiting the amount of water that is available to the plant can limit the amount of carbon assimilation and hence yield. Cell expansion is the most sensitive and typically the first cell process (Figure 2.9) to be affected by water stress (Hsiao *et al.*, 1976). Leaf area is directly affected by cell expansion hence a reduction in expansion of cells will reduce leaf area. Reduction in the leaf area will, in turn, lead to a reduction in the carbohydrate production. After prolonged water stress, suppression of cell expansion can lead to suppressed cell division and hence slowing of leaf initiation (Hsiao *et al.*, 1976).

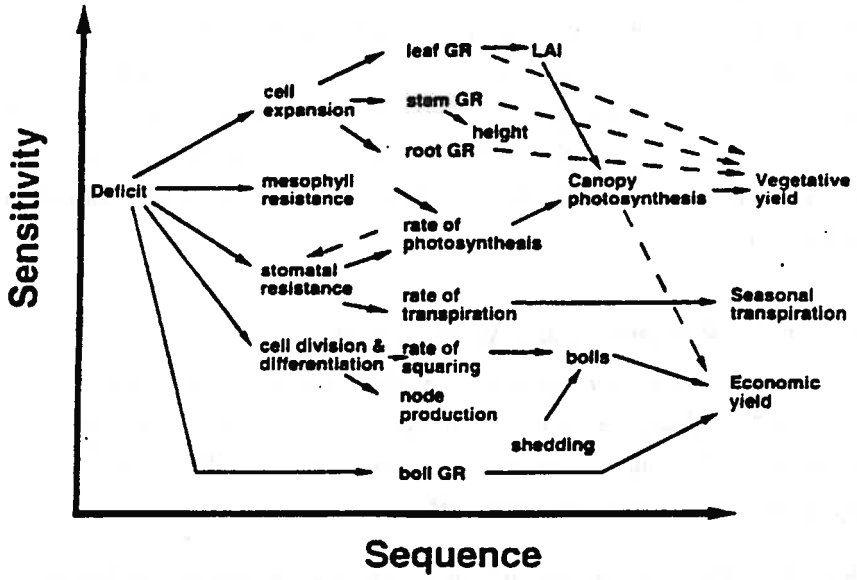


Figure 2.9. Sensitivity and sequence in water stress: the process involved in development, transpiration and economic yield. Source: Hearn (1994).

As water stress increases, stomatal closure can be expected, thus reducing CO_2 assimilation. More severe water stress can result in changing the orientation of the leaf in relation to the sun, i.e. wilting which reduces the radiation load on the leaf (Hsiao *et al.*, 1976).

Visual signs of moisture stress in cotton are wilting, a chance in colour from a light green associated with new growth to a dark green/blue and flowers closer to the top of the plant for moisture deprived cotton. Unfortunately, by the time these visual observations are easily seen, the detrimental effects, i.e. yield reduction, of water stress have already been imposed on the plant by this stage and they are often irreversible.

Reducing the water available to the cotton plant can reduce its leaf area, stem (plant height) and root growth in that order (Figure 2.9). Fruiting structures, particularly larger bolls are among the last to suffer water stress. As cotton is adapted to cropping from a drought tolerant plant (Hearn 1994), there are certain process that are not necessarily normal. Cotton that has an ample water supply will tend to partition assimilates into vegetative growth at the sacrifice of younger reproductive structures (squares) (Figure 2.5). In dry conditions vegetative growth is terminated and assimilates are directed towards older fruit (bolls), once this process in place it is slow to be reversed, even in the presence of ample water (Hearn 1994). The process is usually not reversed until fruit is matured and then vegetative growth recommences. Therefore, for maximum cotton production soil water ideally should be maintained continuously in a range that allows the plant to grow well, but under a mild water stress. There are trigger points in water levels that cause the aforementioned effects to occur. Knowledge of these points theoretically allows deficit irrigation to be implemented without reducing yield.

2.4.2. Timing of Water Stress to Maximize Yield

Table 2.3 outlines cotton water requirements through its growth stages for a well yielding crop. There is ample argument as to which of these stages will result in either yield reduction or enhancement. These differences are due to the wide variation of climates in which it is grown and the disparity in varieties (Hearn 1994).

Table 2.3. Crop development and water use at Narrabri Agricultural Research Station (Anon 1996).

Stage of development	Days from planting	Calender date	Daily water use (mm)
Emergence	7-12	mid October	
First squares	50-60	late Nov/early Dec	1-2
First flowers	75-85	late Dec	2-4
Peak flowering	100-130	mid Jan- mid Feb	3-8
First open boll	130	mid Feb	8
Last effective flower	140-150	late Feb	8-4
Cut-out	180-200	early April	1-2

Despite this uncertainty it is generally agreed that the most sensitive time for water stress is pre-flowering (Prieto and Angueira 1999; Anac *et al.*, 1999; Hearn 1994) as it is during this time that all fruiting structures are pre determined (Constable and Gleeson 1977). Least yield reduction from water deficit have been found when applied in the peak flowering and yield formation stages as opposed to the vegetation or ripening stages (Doorenbos and Kassam 1979). Contrary to these findings de Koch *et al.* (1993) concluded that water deficit stress at the end of effective flowering during peak boll fill had the greatest effect on yield.

2.4.3. Deficit and Drip Irrigation

Deficit irrigation is essentially irrigating the crop at a level lower than its demand. This subject has been well addressed due to the growing need for increased food production and the limited irrigation supply in many of agricultural production areas (Dargie 1999).

Several experiments have been carried out with drip irrigation examining the effect of deficit irrigation. Fangmeier *et al.* (1989) compared three rates of applied water to a cotton crop (0.6, 1.0 and 1.3 times estimated consumptive use). The results found an almost linear relationship between applied water and yield. However the 1.0 times consumptive use treatment gave the greatest water use efficiency.

In a similar study on cotton, Hutchmaker *et al* (1995) looked at the effect of deficit irrigation applied during peak flowering and boll fill (Figure 2.10). They used irrigation treatments that were a percentage of estimated crop water use (from 60-100%). Peak yields were achieved with 700 to 800 mm of crop water use. However, greater than 200 mm of stored soil water were utilised for all treatments which represented about one quarter of the final crop water use. Results are also displayed (Figure 2.10) for a previous experiment by Phene *et al* (1992) which involved a much wider range of applied water on the same site and a polynomial response was observed. These results indicate that over-watering cotton may lead to a reduction in yield, as was observed by Hearn and Constable, (1984) and Hearn (1994).

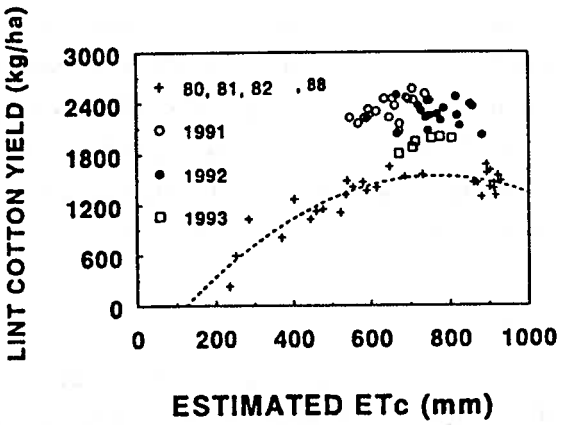


Figure 2.10. Lint yields as a function of ET, Comparison of studies by Phene *et al.* (1992) in 1980, 1981, 1982, 1988 (2nd order polynomial curve fit shown) and Hutchmaker (1995) in 1991-1993. Source: Hutchmaker (1995)

2.5 Conclusions

Hardsetting soils are the second most common soil type used for cotton production in Australia. A range of amelioration techniques have been tested with very few showing long term solutions. Another solution that has been proposed to overcome the problems of irrigating hardsetting soils is SDI. Unfortunately there is a dearth of information of drip irrigation management on hard red soils. Most of the work has been reported in the last two years, focusing mainly on soil water movement and wetting patterns. From this work it is evident that there are limitations with drip irrigation on hardsetting soils particularly in relation to lateral water movement. The findings show that drip is not a soil independent system and hence soil type should be a major consideration in system design and management (irrigation interval and frequency).

Since lateral water movement is limited on these soils, difficulties may occur with 2 m lateral spacings. The calculation of available water capacity under drip irrigation is also more complicated than in a furrow irrigation system as not all of the soil will necessarily be wet by the drippers. For example Battam *et al* (2000a) found that for a soil with a field capacity of approximately 60mm and a lateral drip tape spacing of 2 metres, could be limited to around 20 mm as only 1/3 of the soil is wet by the dripper. This has some very important implications for irrigation management, with small (~ 12 mm) frequent (daily) irrigation events being required during peak crop demand. It must also be remembered that irrigation

water reached the bottom of the root zone after approximately 12 mm application, hence application of greater amounts than this can result in deep drainage losses.

Currently there is conflicting data as to over irrigating and its effect on cotton production. It has been stated that generally "more water equals more cotton" (Hearn 1994), but other experiments found over irrigating can result in excessive vegetative growth and reduce yield. To date conclusive data on irrigation timing and deficit on cotton production is conflicting which is likely to be due to the wide range of cotton varieties and climates in which it is grown (Hearn, 1994). Guidelines are needed if farmers are to achieve maximum cotton yields with SDI and these are clearly lacking in relation to SDI on hardsetting soils.

To determine the level of crop water stress applied by irrigation management it is crucial to be able to estimate the crop water use (evapotranspiration). However while some local calibrations have been conducted in Australia to adjust the aerodynamic component of the ET calculation (da Rosa *et al.*,198?; Meyer 1999), the use of weather data for scheduling cotton irrigation is not widely used. Therefore, validation of the equations currently used for calculating ET are required for achieving yield maximising irrigation strategies.

3 Methods

Hardsetting soils can be difficult to irrigate with surface irrigation techniques. Subsurface drip irrigation (SDI) is a potential alternative to surface irrigation. However minimal guidelines are in existence on how to manage SDI in regards to scheduling and yield results. Therefore, a field experiment was conducted with the aim of providing such guidelines. The field experiment was then set up at 'Bellevue' Warren to investigate the effects of under and over irrigating cotton to determine the potential daily crop evapotranspiration to provide these guidelines.

3.1 Experiment summary

The first two years of the project concentrated on collecting data from existing drip irrigation systems in the Macquarie and Darling regions. During this phase it became obvious that low yields were a major impediment to the adoption of micro irrigation in cotton and that irrigation scheduling was a major reason for the low yields. At the same time, the area of drip irrigated cotton in the Macquarie Valley on hard-setting red soil increased threefold.

We decided to establish a field experiment on an area that could easily be transferred to a commercial scale. Consequently, an experimental site was selected on the commercial cotton farm 'Bellevue', Warren NSW. The site location on the farm was selected because of its soil uniformity which was assessed using an EM survey of all drip irrigated fields on the farm (see Appendix 2). Soil within the experimental area was classified as a Red Chromosol, for a full profile description see Appendix 3 An area of approximately 10 hectares was selected and was divided into plots of the order of 0.5 ha. The experiment was located on one side of a field that had been irrigated with subsurface drip irrigation for 4 seasons prior to the setup of the experiment. Costs to establish the experiment were met by John and Ros OBrien however, as it was already drip irrigated, most of the pipes and valves were in place before the experiment began.

The site was also used for other drip irrigation experiments. John Friend (Dept. of Agriculture, Trangie) sampled from the experimental site in his study of deep drainage study under drip irrigation. Mick Battam investigated the soil hydraulic properties of the site as part of his PhD thesis. Christopher Main and Charles Borthwick used the site to conduct field experiments for their undergraduate degree thesis.

The experimental treatments used in this study were determined after meetings with Dr Brian Hearn, Dr Steve Milroy and Dr Sunil Tennakoon of the Australian Cotton Research Institute (ACRI) in Narrabri and Dr Bruce Sutton of the University of Sydney. Gavin Melville (Dept. of Agriculture, Trangie) was also consulted to ensure that the design would be efficient from a statistical perspective.

The design of the field experiment was a randomized complete block design with 4 blocks and 4 treatments (Figure 3.1). Each plot was 16 rows of cotton spaced 1 m apart. Treatments were:

- 125%- 125% of estimated crop water use for previous day was applied each day.
- 100%- 100% of estimated crop water use for previous day was applied each day.
- 75%- 75% of estimated crop water use for previous day was applied each day.
- 50%- 50% of estimated crop water use for previous day was applied each day.

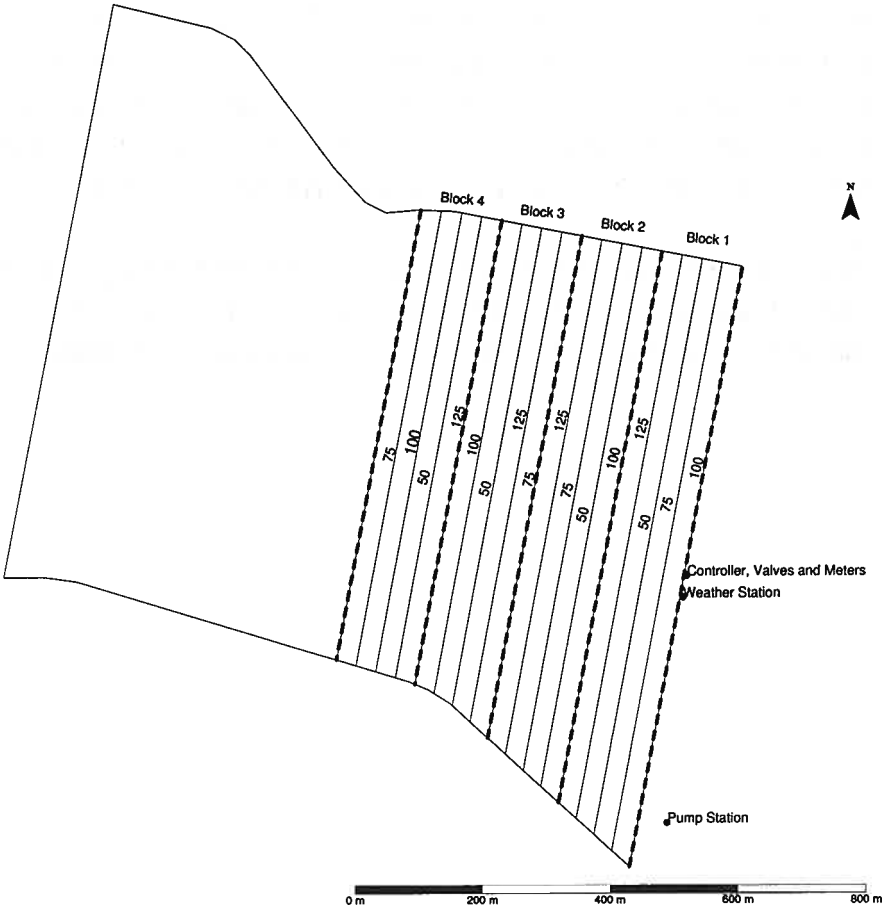


Figure 3.1. Layout of irrigation treatments and drip irrigation infrastructure at 'Bellevue', Warren.

Crop water use was estimated using the FAO modified Penman-Monteith equation which used input data from a weather station at the edge of the field. The accuracy of predicted crop water use was monitored weekly by measuring changes in soil water content with a neutron moisture meter. Changes in profile soil water were used to modify the crop factor for the following week. Investigations conducted by Battam *et al.*, (2000a & b) into the wetted pattern of the soil beneath drip emitters was used to estimate soil water content in conjunction with the neutron moisture meter data.

3.2 Drip Irrigation System Description

Drip irrigation was originally installed in the field in 1994. Prior to this the field consisted of furrow irrigated cotton (field orientation North / South, fall 1 in 800). In August 1998 the field was converted into an experimental site by the installation of new sub-mains and modification of the existing flushing mains. This system allowed application of water separately to each of the 4 treatments shown in Figure 3.1. A Gal Compact® controller was installed to control water applied to each treatment through solenoids and hydraulic valves. Four water meters were also installed to measure water applied to each treatment.

The water was applied through the Netafim subsurface dripline, Ozline 135®. Emitters were spaced at 60 cm that deliver 1.15 l/hr with 10 m water head (0.1 MPa) pressure. The tape was laid at 2 m spacing (Figure 3.2), which equates to an application rate of 1 mm/hr.

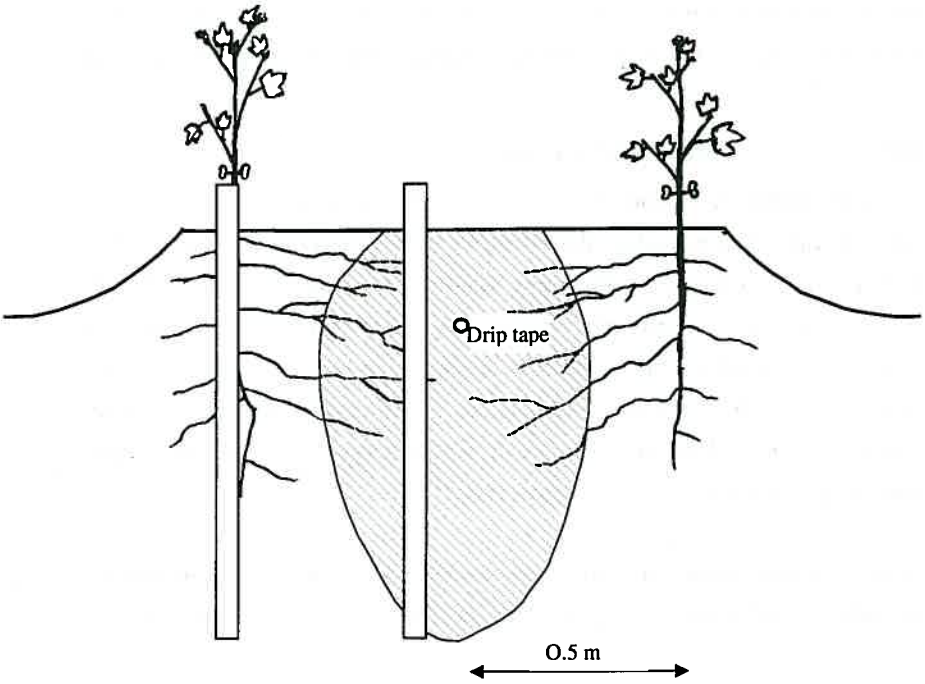


Figure 3.2. Relative location of drip tape, cotton plants and neutron probe access tubes in field experiment at 'Bellevue', Warren. Plant line is 0.5 m from tape. Neutron moisture meter access tubes were located next to drip tape and in plant line on left. Hatched area is soil estimated to be wet after 12 mm irrigation.

3.3 Irrigation scheduling

The basis of the irrigation scheduling for the 100% treatment was to replace the water used by the crop on the previous day. The crop water use was estimated with a weather station using the Penman Monteith equation and a crop factor (Allen *et al*, 1998) as described in Table 3.1.

Table 3.1 Lengths of crop development stages and the corresponding crop coefficients. Source: Allen *et al* (1998).

	Initial	Crop Development	Mid-season	Late season
Stage length (days)	30	50	60	55
Crop Coefficient (K_c)	0.35	0.35 – 1.15	1.15	1.15 – 0.7

Soil water was monitored weekly with a neutron moisture meter. A decline in soil water content in soil next to the drip tape (access tube next to tape in Figure 3.2) in the 100%

treatment was assessed as an underestimation of the crop factor. Similarly, an increase in soil moisture content next to the drip tape in the 100% treatment was assessed as an over-estimation of the crop factor. The crop factor was then adjusted for the following week.

3.4 Crop management

The crop was managed to minimise or eliminate stress from nutrient deficiency, disease or insect damage. This was achieved by managing the crops in a manner similar to the commercial practices used on surrounding fields including watering up the seeds with only the exception of the in-crop irrigation treatments. This system worked well except for application of growth regulators, which are applied to restrict excess vegetative growth that occurred in the 125% treatment in both seasons. In this case the application of growth regulator was delayed until the latest time these growth regulators are normally applied and a uniform application was made to all treatments.

Agronomic inputs for both seasons are listed in Table 3.2, while insecticides applied are listed in Table 3.3 and Table 3.4 for the 1999/2000 and 2000/2001 seasons respectively.

Table 3.2. Agronomic inputs for drip irrigation trial on 'Bellevue', Warren.

Operation		1999/2000	2000/2001
Variety		Sicala 40	Sicala V3 Roundup Ready Ingard
Seed density		18 seeds/m	16 seeds/m
Planting date		17/10/1999	30/9/2000
Planting chemicals:	Herbicides	Stomp (pendimethalin) 3 l/ha (50% band)	Stomp (pendimethalin) 3 l/ha (50% band)
		Diuron 1 l/ha (50% band)	
	Insecticides	Temik (aldicarb) 3 kg/ha	Temik (aldicarb) 3 kg/ha
Fertilizer	Pre-plant	30 kg N/ha as NH_3 (Anhydrous Ammonia)	30 kg N/ha as NH_3 (Anhydrous Ammonia)
		12 tonnes/ha composted gin trash	12 tonnes/ha composted gin trash
	Planting	DAP 25 kg/ha (di-ammonium phosphate)	DAP 25 kg/ha
	Post-plant		22 kg N/ha as urea 3 kg P/ha as phosphoric acid
Post plant weed control	Herbicide	6/12/1999 Staple (pyrithiobac sodium) 120 g/ha	8/11/2000 Roundup-Ready Roundup (glyphosate) 2 kg/ha
		15/12/1999 Shielded spray with Roundup CT (glyphosate) 2 l/ha	
	Cultivation	7/12/1999	18/12/2000
	Chipping	10/11/1999	12/1/2001
Growth Regulant		19/2/2000 Mepiquat chloride 1 l/ha	16/2/2001 Mepiquat chloride 1 l/ha
Defoliation		7/3/2000 Dropp Ultra (Thiazuron + Diuron) 160 ml/ha Prep (Ethephon) 1.5 l/ha DC Tron 2 l/ha	14/3/2001 Dropp Ultra (Thiazuron + Diuron) 60 ml/ha DC Tron 2 l/ha
		14/3/2000 Prep (Ethephon) 1.75 l/ha	19/3/2001 Prep (Ethephon) 2 l/ha
Harvest		2/5/2000 50%, 75% and 100% treatment 12/5/2000 125% treatment	24/3/2001

Table 3.3. Insecticides applied to drip irrigation trial on 'Bellevue', Warren in the 1999/2000 season.

Date	Target insect	Product	Chemical group	Rate (/ha)
29/11/99	Heliothis	Envirofeast	N/A	1 kg
6/12/99	Heliothis	Tracer	Spinosyn	150 g
5/1/00	Heliothis	Karate ULV	Pyrethroid	3.5 l
12/1/00	Heliothis	Predator 300	Organophosphate	5 l
21/1/00	Heliothis	Fastac 100	Pyrethroid	500 ml
		Predator 300	Organophosphate	1.5 l
31/1/00	Heliothis	Curacron flexi	Organophosphate	4 l
		Folidol M500	Organophosphate	2 l
8/2/00	Heliothis	Karate EC	Pyrethroid	85 ml
		Lanate L	Carbamate	1.5 l
18/2/00	Heliothis	Tracer	Spinosyn	200 ml
29/2/00	Heliothis	Curacron flexi	Organophosphate	4 l
		Pegasus	Thiourea	600 ml

Table 3.4. Insecticides applied to drip irrigation trial on 'Bellevue', Warren in the 2000/2001 season.

Date	Target insect	Product	Chemical group	Rate (per ha)
23/11/00	Thrips/ Aphids	Regent	Fipronil	0.063 l
14/12/00	Heliothis	Tracer	Spinosyn	0.20 l
9/01/01	Heliothis	Agrimec	Avermectin	0.30 l
	Mites	Steward	Carbamate	0.65 l
24/01/01	Heliothis	Karate EC	Pyrethroid	0.085 l
	Aphids	Agrimec	Avermectin	0.40 l
		Dimethoate 400 EC	Organophosphate	0.50 l

3.4.1. 1999/2000 Season Summary

Cotton seed was planted on 17/10/1999 and flood irrigated to wet up the seeds. The crop was then established with an acceptable plant stand two weeks later than the optimum time.

Cool conditions prevailed during November and December delaying the crop progress. Treatments were imposed in early December, with a week of rain over the Christmas New Year period wet the soil in all treatments to field capacity. Warmer and drier weather prevailed in January and February resulting in differences in soil moisture and plant growth between treatments. The effects of the treatments started to become visible at the end of January and become more obvious as the season progressed. The whole experiment was managed uniformly throughout the season.

The last irrigation was applied in early March. Prior to this the crop had received 210 mm of cumulative rain from planting. A further 270 mm fell between the last irrigation and harvest. Rain during the harvest delayed the picking of the 125% treatment by 10 days.

3.4.2. 2000/2001 Season Summary

In the 2000/2001 season the experimental plot was planted on the 30/9/2000 and irrigated with Fexiflume® (irrigation piping) with more than 2 Ml/ha used to achieve germination. The crop germinated on the 12/10/2000 and established with an acceptable plant stand.

Significant rain of 240 mm fell in late October and November. This rain delayed the implementation of the treatments until mid December. At the same time a nearby water storage was filled. Water from the storage seeped beneath the experimental site and supplied water to plants on the southern and eastern side of the site. This effect became evident in the middle of January and the extent of seepage was evident in an aerial image of the site recorded in early February (Appendix 5).

Good cotton growing conditions then prevailed for the remainder of the summer. In January problems were encountered with a pump failure on two occasions causing the crop to miss one day's irrigation. The effects of the treatments started to become visible in the middle of January and became more visible as the season progressed in a similar pattern to the previous season.

Apart from the irrigation treatments, the experiment was managed uniformly. The last irrigation was applied on the 6/3/2001. Another 60 mm fell between last irrigation and picking, but no rain fell during picking.

3.5 Measurements

3.5.1. Applied Water

The volume of water applied to each treatment was metered and recorded each day. Volumes were recorded in cubic metres and converted into depth of water applied (mm) by dividing the volume of water applied by the area of each treatment.

3.5.2. Soil Water Content

Volumetric soil water content (θv) was measured with a Campbell Pacific Nuclear 503 neutron moisture meter (NMM) (Martinez, CA, USA), inserted into aluminium access tubes. Single 15 second readings were recorded at five depths: 20, 30, 50, 70 and 90 cm. Readings were taken in 64 tubes, with four access tubes in each treatment, two in the plant line and two within 10 cm of an emitter (Figure 3.2). Readings were taken weekly from the start of December until the crop water use declined to minimal levels in March. Each set of readings

was taken at the same time of day between 7 am to 9 am. Daily irrigation application commenced after the neutron moisture meter readings were taken.

Standard counts were recorded at the start and finish of each season. The Trangie–Warren combination equation (McKenzie *et al.*, 1990) was used to calculate profile water content from the neutron moisture meter readings.

$$\theta_v = -1.60 + 0.707n \qquad 6.3.1$$

where θ_v = volumetric water content and n = neutron count rate ratio (field count divided by standard count).

In the 2000/2001 season two neutron probe readings were taken on the same day to determine the sensitivity of the probe to daily changes in soil water content. A reading was taken in the morning (between 7 and 9 am) and a reading taken in the afternoon (between 6 and 8 pm). No water was applied between the two readings.

3.5.3. Water Balance

The accuracy of ETcrop predicted by the Penman-Monteith equation (Allen *et al.*, 1998) was tested for each season by comparing changes in total profile water content measured using the NMM with the change in total profile water content predicted from water use and water application. The total profile water content was calculated as:

Total profile water = 0.7*Plant line profile water + 0.3*Tape profile water. 3.1

We assumed that the ratio between the contribution of plant line and tape neutron moisture meter measurements would be 0.7 and 0.3 respectively. The rationale was obtained from an estimate by Battam *et al.* (2000a) who found that the maximum width of the zone wet by drip irrigation was no more than 60 cm and thus about 33% of the soil would have a water content unrepresented by the tape measurements..

The predicted profile water content was calculated:

Change in profile water = Water applied + 0.7*rainfall – predicted crop water use 3.2

where 0.7 is chosen as the effective rainfall ratio for the site.

3.5.4. Canopy Temperature (2000/2001 season only)

Canopy temperature was determined using an infra-red thermometer. Readings were taken at three times between the end of December and the middle of January. The thermometer was held at 45° to the crop ensuring that only canopy was in the field of view and a recording taken. In each plot five measurements were taken in two adjacent rows (ten measurements per plot total). Measurements commenced at 7 am on each recording date.

3.5.5. Leaf Water Potential (2000/2001 season only)

A second measure of plant water deficit stress was leaf water potential. Leaf water potential was measured on the youngest, fully expanded leaf of five plants in one replicate of each treatment using a Scholander pressure chamber (Scholander *et al.*, 1965). Measurements were taken starting at 7 am on 11/12/2000, 19/12/2000, 29/12/2000 and 30/12/2000. Air temperature was recorded from the nearby weather station.

3.5.6. Plant Establishment

Plant establishment was variable in both years, so counts of plant emergence were taken to determine sites of average plant density for use in plant mapping and fruit counts in the 1999/2000 and 2000/2001 seasons respectively. Counts of plant emergence were taken from 10 × 1 m row lengths in the centre 8 rows of each plot. Counts occurred in the south, centre and north of the plots in 1999/2000, giving a total of 30 counts of plant emergence in each plot.

The centre of the plots was selected for measurements in 1999/2000, plant density counts were taken in the same area in the 2000/2001, and determined adequate for measurements.

3.5.7. Plant Mapping

1999/2000 season

Eight plants per plot were monitored through the season for height, number of nodes and fruiting site development. An area of one square meter was marked and plants thinned to 7 per linear metre. Two plants in the centre of the metre were marked and mapped. If the marked plant was tipped out (had its primary growing point removed) before the end of December a new plant was selected as the closest non tipped out plant of a similar size.

Fruit retention and development was recorded as the date each of the components according to the following criteria:

- Square ~ date square visible (greater than 2 mm diameter)
- Flower ~ date of anthesis
- Boll ~ date 2 cracks appeared in bracts
- Missing ~ date of loss of fruiting structure - if at all

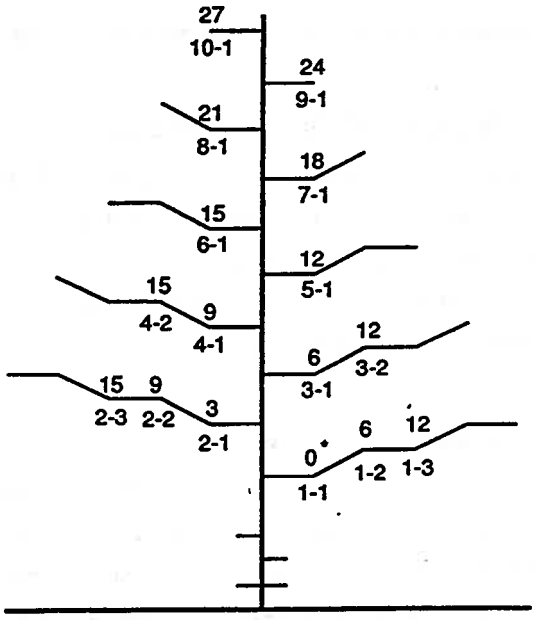


Figure 3.3 Typical cotton plant structure and flowering intervals. Expected bloom date (days from first bloom) over fruiting position number. Source: Rhone Poulenc.

Fruit was labelled as per Figure 3.3, where the first number refers to the main-stem node and the last number refers to the position on the fruiting branch. Even though the plants were only inspected on a weekly basis, it was possible to estimate a few days back in time according to leaf, fruit or scar size and colour (Constable, 1991). Fruit retention was determined as the number of bolls harvested (see 'boll harvesting' below) divided by the number of fruiting positions formed. Once the plants were harvested they were pulled from the ground and an assessment was made of the root development. A score was given to the roots from 1 for good root development to 5 for poor development (McKenzie, 1998).

Fruit Counts (2000/2001 season)

The number of fruiting structures was counted at weekly intervals from early December until early March. Fruit counts were taken from 2 plants in 4 locations in each plot. Plants were tagged, so counts were made on the same plants each week unless plants were tipped out

before 14/1/1. In this case, an adjacent plant that was not tipped out was used for subsequent counts. Counts were taken from the same row used for the 1999/2000 season plant mapping and from areas where the plant density was 7 plants per linear metre. The location of the plant monitoring changed from one season to the next because the plant density varied across the experimental plots.

Boll Harvesting

Each plant that was mapped in both seasons was hand harvested. In the 1999/2000 season each boll was harvested, weighed and its position on the plant recorded. In the 2000/2001 season bolls from each plant were harvested and weighed, number of bolls and boll weight per plant were then recorded.

Lint Yield

Lint yield was estimated using three techniques over the two seasons that cotton was grown. Total seed cotton (lint, seed and some trash) mass harvested with a cotton picker was recorded for both seasons. Hand picking was also conducted in the 2000/2001 season. Variation in yield across each plot was recorded in the 2000/2001 season with an AgLeader® yield monitor.

The total weight of machine picked cotton of each plot was determined using scales. The procedure was to weigh the picker before and after it picked 8 of the 16 rows in each plot. All the cotton picked from each treatment was placed in one module for transport to the cotton gin. The module was weighed before being delivered to the gin, which gave a check of the total mass of cotton harvested from each treatment. The seed cotton weights were then multiplied by the average turnout (lint weight divided by seed cotton weight) for the field to obtain lint yield.

Hand picking was carried out in each plot before machine picking in the 2000/2001 season. Five metres of row was picked at two locations in each plot. The areas where plant counts and plant mapping data were recorded were within the areas that were hand picked.

The yield monitor used in the 2000/2001 season measured seed cotton flow from the picking heads into the picker basket. This data, combined with location information recorded with a GPS receiver allowed yield estimates to be made at 2 second intervals during machine picking. A map produced from this data gave the pattern of yield variation across the experimental site.

Hand Ginning

Hand harvested samples were taken to the Australian Cotton Research Institute at Narrabri where they were weighed, ginned individually through a saw tooth gin and the resulting lint weighed. From each lint sample, a sub sample of 100 g was taken and tested using both the Zellweger Uster HVI 900 (HVI) and the Shirley Fineness Maturity Tester 3 (FMT3) to determine length, uniformity, micronaire, extension, colour, colour grade, and yellowness.

3.5.8. Other Plant Measurements

Plant Height and Number of Nodes

Each plant that was plant mapped (see plant mapping and fruit counts below) in both seasons was also monitored to determine height and number of nodes. Height was defined as the distance from the base of the plant to the growing tip. Nodes were counted when the first leaf was 2 cm diameter.

Leaf Area Index (LAI)

LAI was measured approximately weekly from mid December to mid March. Two samples of one linear metre were harvested per plot. Each sample was weighed then the leaf area of a subset determined using a planimeter and the subset was weighed. The leaf area was then calculated by multiplying the leaf area of the subset by the ratio of the weight of the subset to the total sample weight.

Destructive Plant Sampling

Destructive plant harvests were conducted, at peak flower and at early boll opening. Two samples of one linear metre were harvested per plot. Samples were weighed fresh, then separated into leaves (less petiole) fruit (squares and bolls) and stems. These components were weighed fresh, dried for 48 hours at 75°C in a dehydrator then weighed dry.

3.6 Statistical analysis

The majority of measurements taken were subjected to analysis of variance using the JMP statistical package (SAS Institute, 2000). Treatment effects are described as significant using the 5% significance level. Comparisons between treatments were tested for significant difference using the least significant difference (lsd) procedure.

4 Results

4.1 1999/2000 Season

4.1.1. Applied Water

The volume of water applied to each treatment (Figure 4.1) was 273, 382, 452 and 545 mm for the 50%, 75%, 100% and 125% treatment respectively. Of this water, 75 mm was applied to each treatment to wet the soil to encourage germination (Table 4.1).

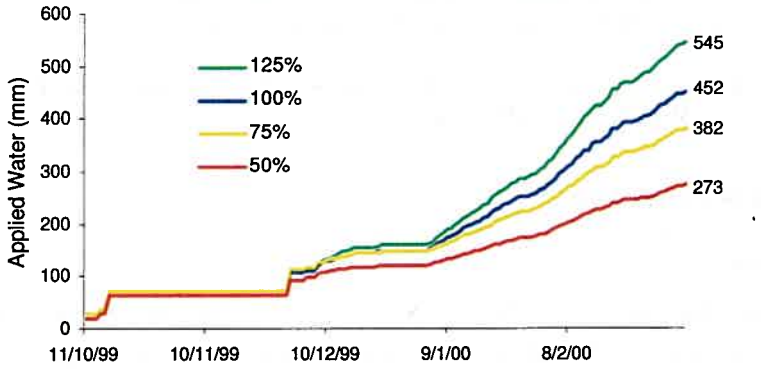


Figure 4.1. Depth of water applied through drip irrigation system in 1999/2000 at 'Bellevue' Warren.

Table 4.1 Applied irrigation water divided into watering up and in-crop amounts in 1999/2000 at 'Bellevue' Warren

	50%	75%	100%	125%
Watering up (mm)	75	75	75	75
In season irrigation (mm)	298	307	377	470
Total irrigation (mm)	273	382	452	545
% of total irrigation required for watering up	27	20	17	14

Little irrigation water was applied to the experiment in the latter half of December because substantial rain fell during that period (Figure 4.2). Rainfall through the crop growing season was erratic, with little rain falling between the large falls that occurred in December, January 26, and March.

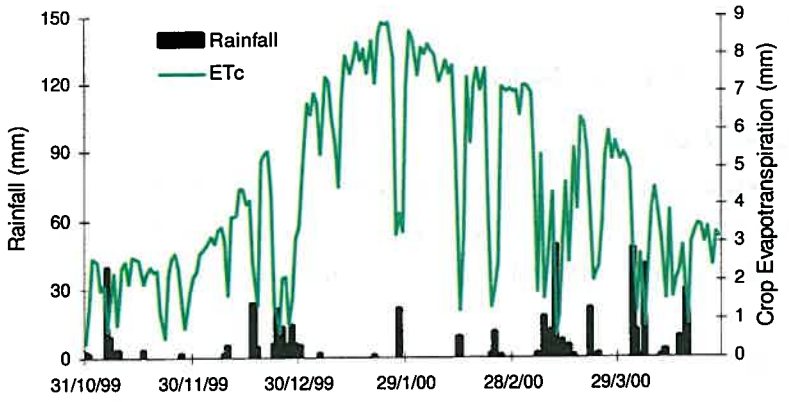


Figure 4.2. Rainfall and estimated crop evapotranspiration measured at 'Bellevue', Warren, in 1999/2000 season.

4.1.2. Soil Water Content

Drip tape

The profile water content next to the drip tape (Figure 4.3) showed little change in the water content of the 100% and 125% treatments through the season. There was no significant difference between profile water content of these 2 treatments for any measurement time through the season.

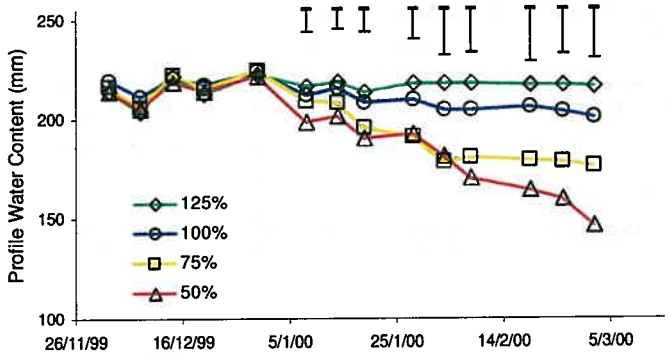


Figure 4.3. Volume of water stored in soil 10 cm from drip emitters and 0 to 90 cm depth at 'Bellevue', Warren. Bars are for 5% lsd.

Profile water content in the 75% and 50% treatments declined from late December until the last reading time, which was taken after the last irrigation event. The 50% treatment was drier than all of the other treatments on 8/1/2000, but prior to this date minimal differences occurred between the 50% and 75% treatments with regards to soil water content close to the

tape. The 75% treatment became drier than the 100% and 125% treatments on 19/1/2000. Both the 50% and 75% treatments remained drier than the 100% and 125% treatments until the end of the irrigation season

Plant line

Rainfall in December wet the soil in the plant line of all treatments, with peak plant line water contents occurring coinciding with rain events over the Christmas period (Figure 4.4). The profile water contents in the plant line in all treatments then declined rapidly until 19/1/2000, at which point the rate of decline slowed. Water from the 40 mm rain that fell on 25/1/2000 did not rewet the soil to a great extent in the zone measured by the neutron moisture meter. There were no significant differences in plant line profile water contents until the 8/2/2000. However, the 125% treatment was wetter than the remaining three treatments on 8/2/2000 and 19/2/2000. The difference between the 100% and 125% treatments was no longer significant on 25/2/2000, while both the 100% and 125% treatments were wetter than the 50% treatment on 2/3/2000.

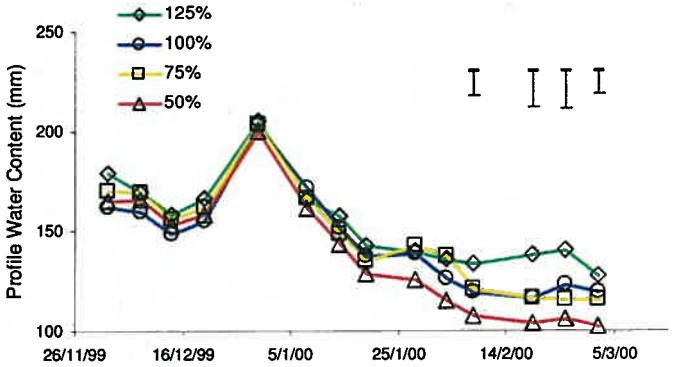


Figure 4.4. Volume of water stored in soil from 0 to 90 cm in the plant line at 'Bellevue', Warren. Bars are for 5% lsd.

Table 4.2 has volumetric soil water contents for all treatments on all sample dates. Significance levels are given between the treatments for each of the depths. Differences in the soil water content were detected from the first readings on the 2/12/1999. After the rainfall event in late December no differences were found in the readings adjacent to the tape. From then on to the 3/2/2000 the differences became apparent down the profile until all depths showed differences between the treatments. Readings taken in the plant line showed the pattern of water extraction tended to be from under the plant first and then into the wetter area of the drip tape.

Table 4.2. Volumetric Soil Water Content (cm^3/cm^3) for all treatments at all depths.

Significance level; NS not significant, * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level for differences between treatments.

Colours represent differing ranges of soil water content where red is dry, green is intermediate and blue is wet as below:

Red: ≤ 0.17 cm3/cm3

Green: 0.17 to 0.22 cm3/cm3

Blue: ≥ 0.2 cm3/cm3

		50%		75%		100%		125%		Sig. Level	
date	depth	plant	tape	plant	tape	plant	tape	plant	tape	plant	tape
2/12/99	20	0.08	0.18	0.09	0.19	0.07	0.20	0.11	0.19	***	NS
	30	0.16	0.23	0.16	0.24	0.14	0.24	0.17	0.23	*	NS
	50	0.26	0.27	0.25	0.27	0.25	0.27	0.25	0.27	NS	NS
	70	0.26	0.27	0.25	0.27	0.25	0.27	0.25	0.26	NS	*
	90	0.25	0.26	0.25	0.26	0.25	0.26	0.24	0.26	NS	NS
8/12/99	20	0.11	0.21	0.13	0.21	0.09	0.21	0.12	0.21	***	NS
	30	0.14	0.20	0.16	0.21	0.13	0.22	0.16	0.20	**	**
	50	0.22	0.24	0.22	0.24	0.22	0.25	0.22	0.24	NS	NS
	70	0.24	0.25	0.24	0.25	0.24	0.25	0.24	0.25	NS	**
	90	0.24	0.24	0.22	0.22	0.25	0.24	0.23	0.23	***	**
14/12/99	20	0.06	0.20	0.06	0.21	0.04	0.20	0.07	0.21	NS	NS
	30	0.13	0.25	0.14	0.25	0.12	0.25	0.14	0.25	***	NS
	50	0.24	0.27	0.23	0.27	0.23	0.27	0.23	0.27	NS	NS
	70	0.25	0.26	0.25	0.27	0.25	0.27	0.25	0.26	NS	NS
	90	0.23	0.24	0.23	0.24	0.25	0.24	0.24	0.24	**	NS
20/12/99	20	0.09	0.20	0.10	0.19	0.09	0.20	0.11	0.20	NS	NS
	30	0.13	0.24	0.14	0.25	0.12	0.25	0.15	0.24	**	NS
	50	0.22	0.27	0.22	0.27	0.21	0.27	0.23	0.26	NS	NS
	70	0.24	0.26	0.24	0.26	0.24	0.26	0.24	0.26	NS	NS
	90	0.23	0.23	0.23	0.24	0.25	0.23	0.23	0.23	**	NS
30/12/99	20	0.19	0.21	0.19	0.22	0.18	0.22	0.18	0.22	NS	NS
	30	0.20	0.25	0.22	0.25	0.21	0.25	0.22	0.25	**	NS
	50	0.24	0.27	0.24	0.27	0.25	0.27	0.25	0.27	NS	NS
	70	0.25	0.26	0.25	0.26	0.25	0.26	0.26	0.27	NS	NS
	90	0.24	0.24	0.23	0.24	0.25	0.24	0.24	0.24	**	NS
8/01/00	20	0.10	0.17	0.10	0.18	0.12	0.19	0.11	0.20	**	**
	30	0.15	0.22	0.17	0.23	0.17	0.24	0.17	0.24	*	*
	50	0.23	0.25	0.22	0.26	0.23	0.26	0.22	0.27	NS	NS
	70	0.23	0.26	0.24	0.26	0.24	0.26	0.23	0.26	NS	NS
	90	0.22	0.23	0.23	0.23	0.22	0.23	0.23	0.24	NS	NS
14/01/00	20	0.06	0.17	0.07	0.18	0.07	0.20	0.09	0.21	NS	***
	30	0.13	0.22	0.14	0.24	0.14	0.24	0.15	0.25	NS	**
	50	0.21	0.26	0.21	0.26	0.21	0.26	0.22	0.27	NS	NS
	70	0.23	0.25	0.23	0.26	0.23	0.26	0.24	0.26	NS	NS
	90	0.22	0.23	0.22	0.23	0.24	0.24	0.23	0.24	***	NS
19/01/00	20	0.04	0.14	0.05	0.16	0.05	0.19	0.06	0.19	NS	***
	30	0.11	0.21	0.12	0.22	0.12	0.23	0.13	0.24	NS	**
	50	0.19	0.25	0.19	0.25	0.20	0.26	0.20	0.27	NS	*
	70	0.21	0.25	0.22	0.25	0.22	0.26	0.23	0.26	***	**
	90	0.21	0.23	0.21	0.23	0.23	0.24	0.22	0.24	**	NS
28/01/00	20	0.04	0.16	0.09	0.17	0.07	0.19	0.07	0.21	NS	**
	30	0.10	0.20	0.12	0.21	0.12	0.23	0.13	0.25	NS	***
	50	0.20	0.25	0.19	0.24	0.19	0.26	0.19	0.26	NS	NS
	70	0.21	0.25	0.21	0.24	0.21	0.26	0.21	0.26	NS	**
	90	0.21	0.23	0.20	0.21	0.23	0.24	0.23	0.24	**	**
3/02/00	20	0.03	0.15	0.07	0.13	0.04	0.18	0.06	0.20	*	***
	30	0.09	0.20	0.13	0.20	0.10	0.23	0.12	0.25	*	**
	50	0.18	0.23	0.19	0.24	0.19	0.25	0.19	0.27	NS	*
	70	0.19	0.23	0.21	0.23	0.20	0.26	0.22	0.27	**	**
	90	0.20	0.22	0.21	0.22	0.22	0.24	0.22	0.23	NS	*
8/02/00	20	0.02	0.13	0.04	0.13	0.03	0.18	0.06	0.20	*	***
	30	0.08	0.18	0.11	0.20	0.10	0.23	0.12	0.25	NS	***
	50	0.18	0.22	0.18	0.24	0.18	0.26	0.19	0.27	NS	***
	70	0.18	0.23	0.20	0.24	0.20	0.26	0.21	0.26	***	**
	90	0.18	0.20	0.18	0.20	0.21	0.23	0.22	0.24	***	**
19/02/00	20	0.01	0.13	0.03	0.15	0.03	0.19	0.06	0.21	**	***
	30	0.08	0.17	0.11	0.20	0.10	0.23	0.13	0.25	**	***
	50	0.17	0.21	0.17	0.23	0.18	0.25	0.19	0.26	NS	***
	70	0.18	0.22	0.20	0.23	0.19	0.25	0.21	0.26	***	**
	90	0.18	0.20	0.17	0.19	0.20	0.23	0.22	0.23	***	***
25/02/00	20	0.03	0.13	0.05	0.15	0.04	0.19	0.08	0.21	**	***
	30	0.09	0.17	0.11	0.21	0.10	0.23	0.13	0.25	**	***
	50	0.17	0.21	0.16	0.22	0.19	0.25	0.20	0.26	*	***
	70	0.17	0.21	0.19	0.23	0.20	0.24	0.21	0.26	***	***
	90	0.18	0.20	0.17	0.20	0.21	0.21	0.20	0.23	**	NS
2/03/00	20	0.02	0.11	0.04	0.15	0.03	0.18	0.05	0.20	***	***
	30	0.08	0.16	0.11	0.20	0.10	0.23	0.11	0.25	**	***
	50	0.17	0.19	0.18	0.22	0.19	0.25	0.18	0.26	NS	***
	70	0.17	0.20	0.19	0.22	0.19	0.25	0.20	0.26	***	***
	90	0.16	0.18	0.17	0.19	0.19	0.23	0.21	0.24	***	***

4.1.3. Water Balance

Trends in the weekly water balance were observed to be similar all 4 treatments until 30/12/2000 (Figure 4.5). These trends were an increase in both predicted and measured profile water contents when rain fell between 14/12/2000 and 20/12/2000, followed by a decrease in profile water content between the cessation of rain on the 30/12/1999 and the recommencement of irrigation on the 5/1/2000.

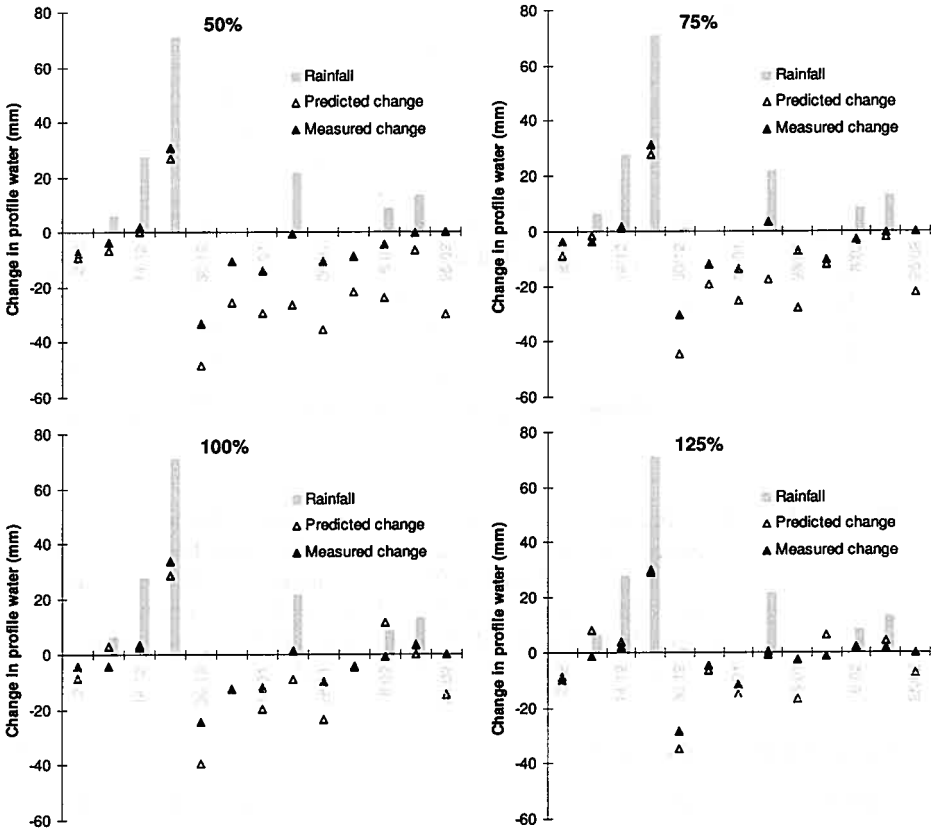


Figure 4.5. Comparison between changes between profile water content measured from one Neutron Moisture Meter reading to the next and changes predicted from water applied, rainfall and crop evapotranspiration predicted according FAO 56 (Allen *et al.*, 1998). Measurements recorded at 'Bellevue', Warren 1999/2000 season.

The balance between predicted and measured profile water contents varied between the treatments, with the 125% treatment generally displaying a predicted profile water content that was greater than the measured change through January and February. Conversely, the profile water content of the 50% treatment during January and February was generally

predicted to be less than that which was measured. It appeared that the predicted and measured profile water contents for the 75% and 100% treatment were intermediate between the 50% and 125% treatments and were generally similar throughout the measurement period.

The correlations between the measured and the predicted changes (Figure 4.6) were r^2=0.687 for the 125% treatment and increased to 0.796 for the 100% treatment and further increased to more than 0.82 for the remaining two treatments.

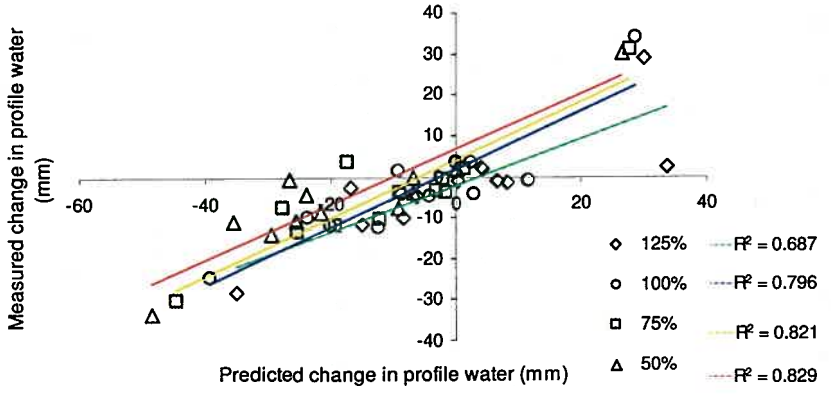


Figure 4.6. Measured against predicted changes in profile water content. Measured changes determined by the change in profile water content from one Neutron Moisture Meter reading to the next and changes predicted from water applied, rainfall and crop evapotranspiration predicted according FAO 56 (Allen *et al.*, 1998). Measurements recorded at 'Bellevue', Warren 1999/2000 season.

4.1.4. Plant Establishment

Plant densities counted in each treatment ranged from 1 to 16 plants/m. However, the average density in each treatment varied little. This is to be expected as treatments were not implemented until after plant establishment. Densities calculated were 7.4 plants/m for the 50% treatment, and 7.2 plants/m for the remaining three treatments. The variable nature of the plant stand was reflected in the standard deviation of 3 plants/m that was recorded for all four treatments.

4.1.5. Number of Nodes

The number of nodes was the first of the measured plant properties to show differences that could be attributed to the irrigation treatments. The 50% and 75% treatments had fewer

nodes than the 100% and 125% treatments from early December through to the end of the season (Figure 4.7). On the 20/12/1999 the 50% treatment had 0.5 fewer nodes than the 100% treatment. The magnitude of differences between treatments increased through January when plants in the 50% treatment were the first to stop producing new nodes. The 75% treatment was the next one to stop producing new nodes, followed by the 100% then the 125% treatments.

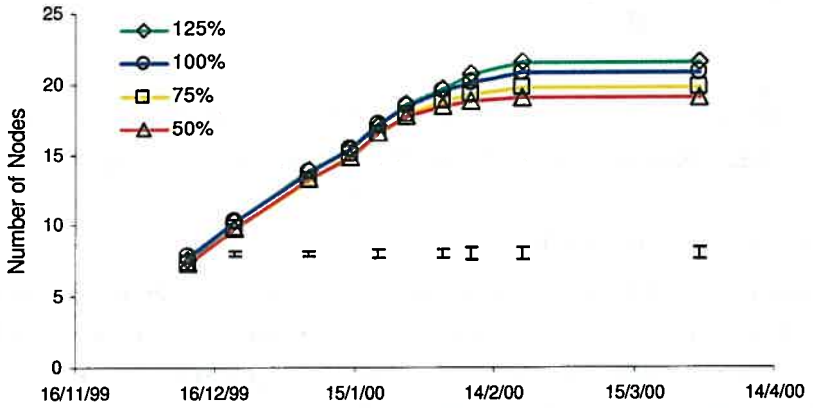


Figure 4.7. Node development at 'Bellevue', Warren. Bars are for 5% lsd.

4.1.6. Plant Height

The plant height followed a very similar pattern to the node development. However, differences in plant height due to the treatments did not become apparent until 29/12/1999 (Figure 4.8). The treatment receiving the most water (125%) was the highest and the treatments that received the least water (75% and 50%) were the shortest.

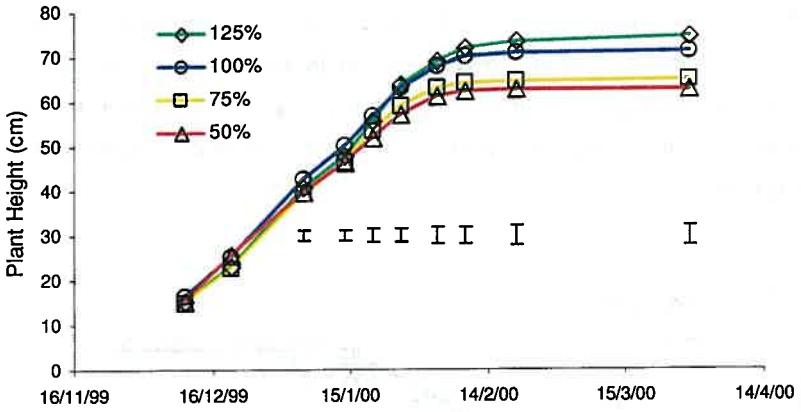


Figure 4.8. Plant height at 'Bellevue', Warren. Bars are for 5% lsd.

4.1.7. Leaf Area Index (LAI)

Leaf area increased between measurement times in all treatments until the 16/2/2000 (Figure 4.9). However the 50% and the 75% treatments tended to have a slower increase in leaf area than the 100% and 125% treatments. The differences were greatest on 16/2/2000 and 20/3/2000 where the 50% and 75% treatments had a smaller LAI than the 100% and 125% treatments. Leaf area remained constant between 16/2/2000 and 20/3/2000 in all the treatments except the 75%.

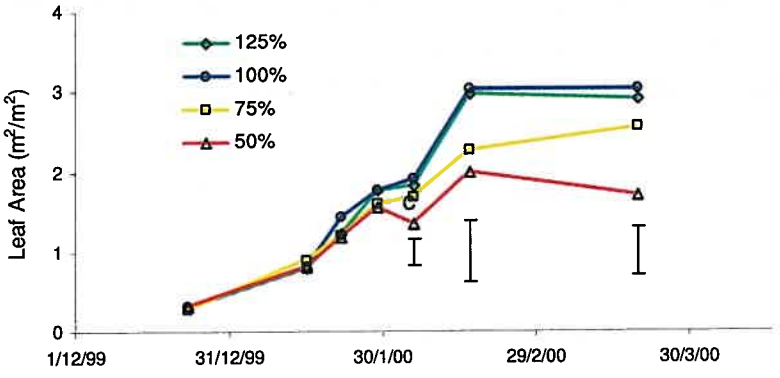


Figure 4.9. Effect of irrigation treatment on leaf area index at 'Bellevue', Warren. Bars are for 5% lsd.

4.1.8. Destructive Plant Sampling

There were no significant differences in the dry weights of the plant components (squares, boll, stem and leaf in the destructive sampling at peak flowering (16/2/2000). However, the weights of leaves, bolls and stems of the 50% treatment was significantly lower than the other treatments on 20/3/2000 (Figure 4.10). There was a consistent but non-significant trend for weights of these components to be greater in the 100% treatment than both the 75% and 125% treatments.

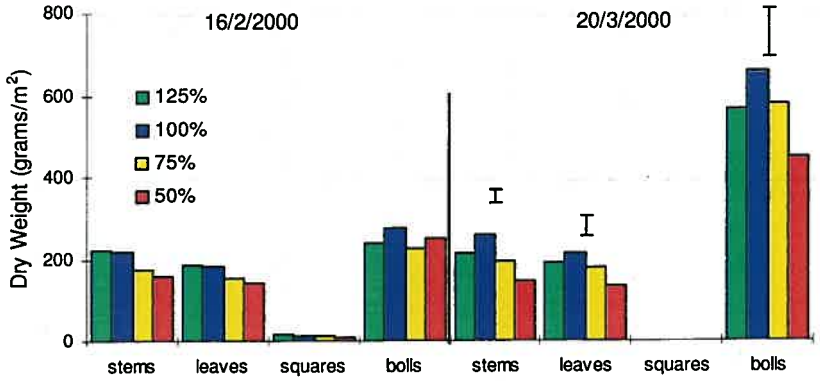


Figure 4.10. Dry weights of plant components on 2 separate destructive harvests at 'Bellevue', Warren. Bars are for 5% lsd.

4.1.9. Plant Mapping

Plant mapping differences between treatments were evident at the top and bottom of the plant but not in the middle. Differences between the numbers of squares were found on the ninth node (Table 4.3) where the 75% and 125% treatment had fewer fruiting positions on position 2 than the 50% or 100% treatments. On node 9 position 3 the 125% treatment had fewer fruiting positions than all other treatments while the 75% treatment had fewer fruiting positions than the 50%. Higher up the plant on node 18 position 2, node 19 position 2 and node 23 position 1 the 125% treatment produced more fruit on these sites than the 50% and 75% treatments. On node 19 position 1 the 100% and 125% treatment has significantly more fruiting positions than the 50% and 75% treatments. On node 20 position 2 the 125% treatment had more fruiting positions than all other treatments.

Table 4.3. Main-stem node and branch nodes showing significant differences in the number of flowers per metre between treatments at 'Bellevue', Warren in the 1999/2000 season.

Fruit	Node	Position	50%	75%	100%	125%	lsd.
Squares	9	2	7.2	6.5	7.0	6.5	0.5
	9	3	7.2	6.1	6.8	5.6	1.0
	18	2	0.5	1.1	1.4	2.5	1.3
	19	1	4.3	5.0	6.3	6.3	1.6
	19	2	0.2	0.5	1.1	2.3	0.7
	20	2	0	0.2	0.2	0.9	0.5
	23	1	0	0.2	0.2	2.0	1.5
Flowers	10	1	6.5	5.6	7.0	5.6	1.1
	13	3	0.7	0.5	2.0	2.0	1.4
	14	3	0.2	0.7	0.2	1.4	0.9
	15	2	2.7	1.4	2.9	4.5	2.1
	16	1	3.8	5.6	5.9	5.6	1.6
Retention	10	1	6.3	11.8	12.6	11.8	0.9
	14	3	0	0	0	0.7	0.5
	15	1	1.6	2.5	0.9	3.4	1.6
	15	2	0	0.2	1.1	1.1	1.0
	19	1	0	0.5	1.1	2.0	1.4
	20	1	0	0	0.5	1.5	0.9
	21	1	0	0	0.2	1.5	1.2

Fruit retention percentage was determined as the number of bolls harvested divided by the number of fruiting positions formed. Differences in the fruit retention tended to be higher up the plant.

Table 4.4 shows the frequency of branches on the plant with none, one, two, or three mature bolls. It was rare for all positions to be filled (~1%) and no differences were found between the treatments. It was more common for all positions to be shed with the 50% treatment than the 125% treatment. The second most common event was where only the first position fruit was retained, with the 75% treatment incurring 5.9% more fruit loss on the second and third positions than the 50% treatment. The first two positions were retained in 13 to 17% of occasions. Shedding of the first and third position fruit showed the 125% treatment lost more fruit in these positions than the 100% treatment.

A graphical summary of fruit count for the 1999/2000 season showing average plant characteristics for number of squares, number of flowers and percentage fruit retention is given in Appendix 4. There were no significant differences in the boll weights between the treatments at any of these categories.

Table 4.4. Frequency (%) of different categories of boll survival on fruiting branches. 'Bellevue', Warren.

Category	50%	75%	100%	125%	lsd.
All positions occupied	1	1	2	1	n.s.
Only first position shed	2	0	1	2	n.s.
Only second position shed	1	0	1	1	n.s.
Only third position shed	13	13	17	14	3
First and second positions shed	1	0	1	1	n.s.
First and third positions shed	8	8	7	11	4
Second and third positions shed	31	37	34	35	6
All positions shed	43	41	38	36	6

Average boll weights and number (Table 4.5) showed that the variation in weights was restricted to the second and third branch positions. On branch position 2 the 50% and 75% treatments had heavier bolls than the remaining treatments however the 50% treatment had fewer bolls than the 100% and 125% treatments. On position 3 the 50% and 75% treatments the boll weights were significantly heavier than the 100% and 125% treatments. Branch position 1 of the 50% treatment had fewer bolls than all other treatments. The 100% treatment also had a greater number of bolls than the 75% treatment.

Table 4.5. Average seed cotton weights per boll (grams) and average boll number per metre on each branch node at 'Bellevue', Warren.

Boll	Branch Position	50%	75%	100%	125%	lsd.
weight	1	6.21	6.18	6.28	6.39	n.s.
	2	5.64	5.16	5.15	4.66	0.46
	3	4.5	4.77	3.33	3.41	1.48
number	1	43	51	58	54	7
	2	23	22	29	29	6
	3	4	2	5	5	n.s.

The seed cotton yield (Figure 4.11) showed that trends in seed cotton mass differences between the treatments below the twelfth node were hard to detect. Above the twelfth node the 50% treatment tended to have less seed cotton.

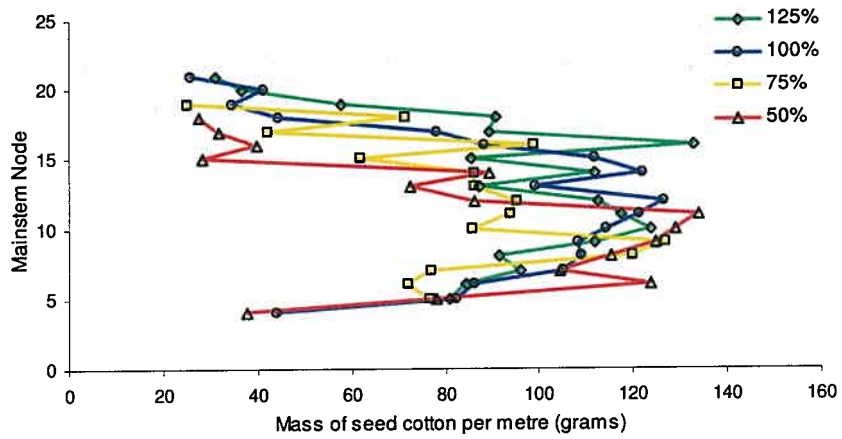


Figure 4.11. Average seed cotton mass by main-stem node at 'Bellevue', Warren.

4.1.10. Yield

The 100% treatment had significantly greater yield than the 75% and 50% treatments (Figure 4.12). There was no significant difference between the yield of 75% and 125% treatments neither was there between the 100% and 125% treatments. An aerial yield map is given in Appendix 5.

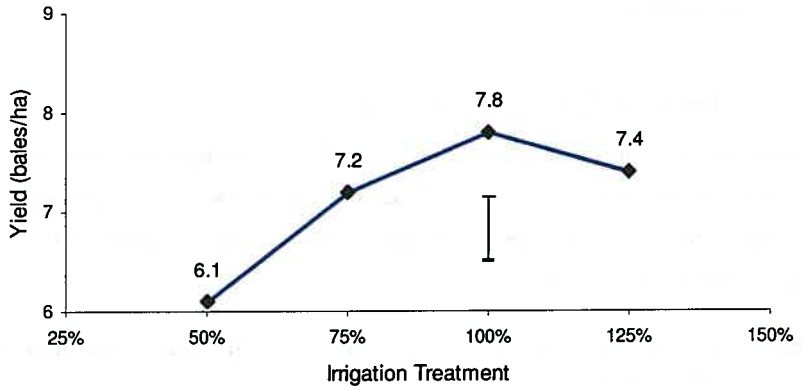


Figure 4.12. Cotton yield measured from picker harvested weights (assuming 38% turnout and 227 kg/bale) 'Bellevue', Warren. Bar is for 5% lsd for cotton yield.

Plate 4.1 Cotton in the 50% treatments on the left and 100% treatments on the right at 'Bellevue', Warren. Note the difference in size of the bushes. Picture taken in March just after initial defoliation.

4.1.11. Cotton Quality

The 1999/2000 season showed some variation in commercial classing. Bales from the 75% and 100% treatments were classed as White Middling (31) and had a discount of $21.54/bale while bales from the remaining treatments were classed as Strict Low Middling (41) and were discounted by $43.05 / bale. The lower quality of the 125% treatment may have been caused by rain damage as a result of the later harvest. The 50% treatment may have had open bolls on the bush for longer than the other treatments due to the earliness of the crop, again exposing it to the weather.

4.1.12. Irrigation-Water Use Efficiency

The decrease in water applied to the 50% treatment was far greater than the decrease in yield, so irrigation-water use efficiency (Table 4.6) of the 50% treatment was greater than the remaining treatments. Irrigation-water use efficiency then declined substantially with increasing irrigation water application.

Table 4.6. Irrigation-water use efficiency (bales/Ml) at 'Bellevue', Warren in the 1999/2000 season.

	50%	75%	100%	125%	lsd
Irrigation-water use efficiency	2.24	1.87	1.73	1.36	0.18

4.2 2000/2001 Season

4.2.1. Applied Water

The volume of water applied to each treatment (Figure 4.13) was 465, 529, 607, and 701 mm to the 50%, 75%, 100% and 125% treatments respectively. A substantial proportion of this water (238 mm) was applied to wet the seedbed to encourage germination of the crop. We applied the majority of the water for germination from the surface using furrow irrigation because Battam *et al.* (2000) found that applying water in excess of about 20 mm from the drip line results in most of the additional water being lost as deep drainage.

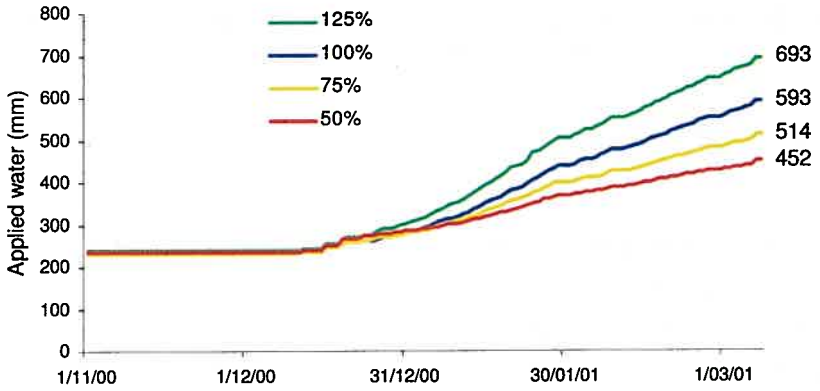


Figure 4.13. Depth of water applied through drip irrigation system in 2000/2001 at 'Bellevue' Warren.

Table 4.7 Applied irrigation water divided into watering up and in-crop amounts in 2000/2001 at 'Bellevue' Warren

	50%	75%	100%	125%
Watering up (mm)	238	238	238	238
In season irrigation (mm)	227	291	369	463
Total irrigation (mm)	452	514	593	693
% of total irrigation required for watering up	51	45	39	34

Most of the rain during the 2000/2001 season fell in October and November (Figure 4.14). Irrigation treatments were imposed in early December, and subsequent rainfall had little impact on the irrigation treatments

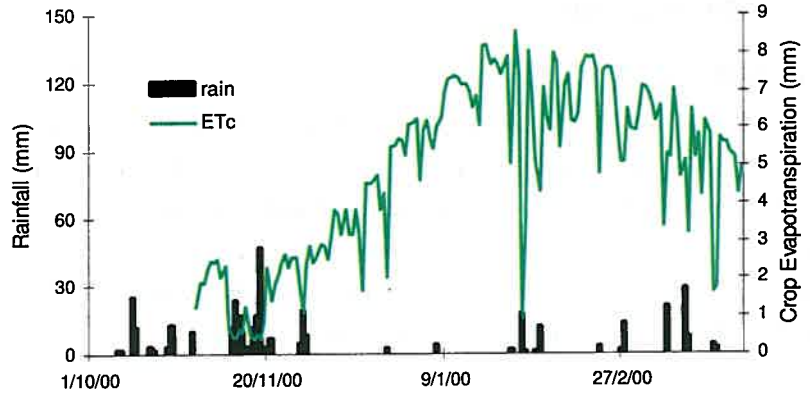


Figure 4.14. Rainfall and estimated crop evapotranspiration measured at 'Bellevue', Warren, in 2000/2001 season

4.2.2. Soil Water Content

Drip tape

The profile water content of the 100% and 125% treatments next to the drip tape (Figure 4.15) declined by about 10 mm from 20/11/2000 to 20/12/2000. These two treatments dried by a further 30 mm from 20/12/2000 until 4/1/2001 (Figure 4.15). At this time, a decision was made to increase the crop factor used to calculate the volume of water to be applied. The profile water content then increased 25 mm between 4/1/2001 and 24/1/2001, and remained relatively constant for the remainder of the season. There was no significant difference between profile water content of the 100% and 125% treatments for any measurement time through the season.

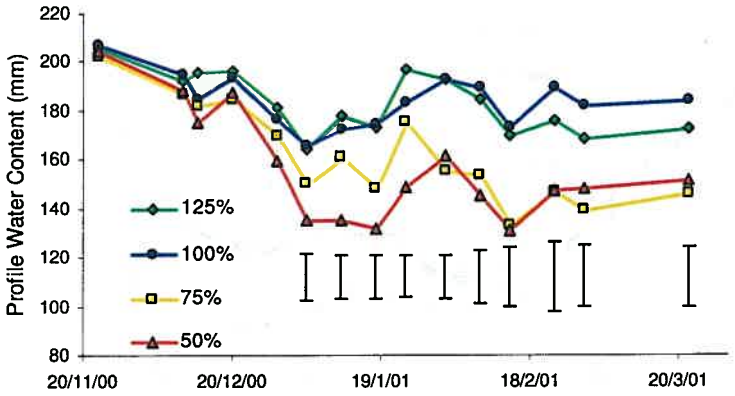


Figure 4.15. Volume of water stored in soil 10 cm from drip emitters and 0 to 90 cm depth at 'Bellevue', Warren. Bars are for 5% lsd.

Profile water content in the 75% and 50% treatments declined from late November 4/1/2001, and then remained relatively constant for the remainder of the season (Figure 4.15). The 50% treatment was significantly drier than the remaining 3 treatments for readings from 4/1/2001 until 24/1/2001. From 1/2/2001 until the last reading on 22/3/2001 both the 50% and 75% treatments were drier next to the tape than both the 100% and 125% treatments.

Plant line

Profile water content in the plant line of all treatments declined from about 195 mm on 23/11/2000 to about 115 mm on 4/1/2001 (Figure 4.16). The profile water contents in the plant line of the 100% and 125% treatments then remained relatively constant for the remainder of the season while the water content of the plant line of the 50% and 75% treatments declined further to about 90 mm on 23/2/2001.

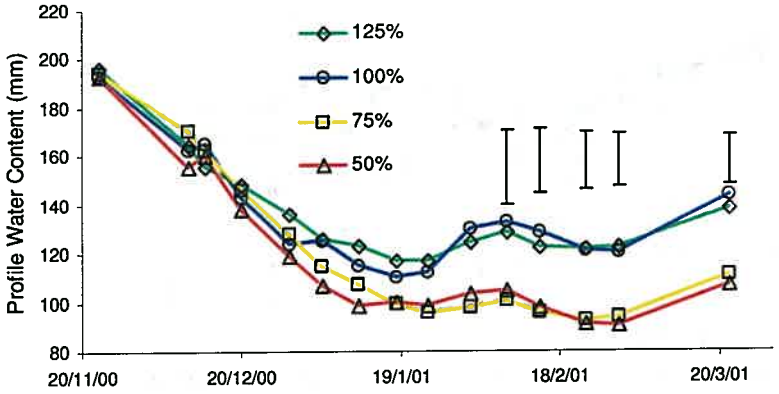


Figure 4.16 Volume of water stored in soil from 0 to 90 cm in the plant line at 'Bellevue', Warren. Bars are for 5% lsd.

The profile water content in the plant line of the 100% and 125% treatments was wetter than the 50% and 75% treatments for all 4 measurement times from the 14/2/2001 to the end of the season. Statistical analysis showed that the 75% treatment was wetter than the remaining 3 treatments on 10/12/2000, however it only contained 6 mm more water than the 125% treatment.

Table 4.8. Volumetric Soil Water Content (cm^3/cm^3) for all treatments at all depths.

Significance level; NS not significant, * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level for differences between treatments. Colours represent differing ranges of soil water content where red is dry, green is intermediate and blue is wet as below:

Red ≤ 0.17 cm3/cm3

Green 0.17 to 0.22 cm3/cm3

Blue ≥ 0.2 cm3/cm3

treatment		50%		75%		100%		125%		Sig. Level	
date	depth	plant	tape	plant	tape	plant	tape	plant	tape	plant	tape
23/11/2000	20	0.17	0.20	0.18	0.20	0.18	0.21	0.18	0.21	NS	NS
	30	0.21	0.24	0.21	0.23	0.21	0.24	0.22	0.24	NS	NS
	50	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.25	NS	NS
	70	0.23	0.24	0.24	0.24	0.23	0.24	0.24	0.24	NS	**
	90	0.23	0.22	0.23	0.23	0.23	0.23	0.22	0.21	**	***
10/12/2000	20	0.08	0.16	0.11	0.16	0.10	0.18	0.10	0.17	NS	*
	30	0.14	0.22	0.17	0.21	0.16	0.22	0.16	0.22	**	NS
	50	0.22	0.24	0.23	0.24	0.22	0.23	0.23	0.24	NS	NS
	70	0.23	0.23	0.23	0.24	0.23	0.23	0.23	0.23	NS	NS
	90	0.23	0.22	0.22	0.22	0.23	0.23	0.22	0.22	**	**
13/12/2000	20	0.09	0.13	0.10	0.14	0.11	0.15	0.09	0.18	NS	***
	30	0.16	0.19	0.16	0.20	0.16	0.20	0.15	0.22	NS	***
	50	0.22	0.23	0.22	0.23	0.22	0.23	0.22	0.24	NS	NS
	70	0.23	0.23	0.23	0.23	0.23	0.24	0.23	0.24	NS	NS
	90	0.23	0.23	0.22	0.22	0.23	0.23	0.22	0.22	NS	***
20/12/2000	20	0.05	0.16	0.07	0.15	0.07	0.18	0.08	0.18	NS	**
	30	0.11	0.20	0.13	0.20	0.12	0.21	0.14	0.22	NS	NS
	50	0.19	0.23	0.20	0.23	0.19	0.23	0.20	0.24	NS	NS
	70	0.22	0.24	0.23	0.24	0.23	0.24	0.23	0.24	NS	NS
	90	0.23	0.23	0.23	0.23	0.24	0.24	0.22	0.22	**	***
29/12/2000	20	0.04	0.12	0.05	0.14	0.05	0.16	0.07	0.16	**	**
	30	0.10	0.16	0.11	0.18	0.10	0.19	0.13	0.20	***	*
	50	0.17	0.19	0.17	0.20	0.16	0.20	0.17	0.21	NS	NS
	70	0.20	0.22	0.21	0.23	0.21	0.23	0.21	0.23	NS	NS
	90	0.22	0.23	0.22	0.22	0.23	0.23	0.22	0.22	**	***
4/1/2001	20	0.03	0.08	0.04	0.11	0.06	0.15	0.06	0.14	*	***
	30	0.09	0.14	0.10	0.15	0.11	0.18	0.12	0.18	NS	***
	50	0.16	0.17	0.16	0.18	0.16	0.18	0.17	0.20	NS	NS
	70	0.17	0.20	0.19	0.21	0.19	0.21	0.19	0.22	NS	NS
	90	0.21	0.21	0.21	0.21	0.23	0.23	0.21	0.21	***	**
11/1/2001	20	0.02	0.10	0.04	0.15	0.05	0.17	0.06	0.16	**	***
	30	0.09	0.15	0.10	0.18	0.10	0.20	0.12	0.20	**	***
	50	0.16	0.17	0.15	0.18	0.15	0.19	0.17	0.21	NS	**
	70	0.15	0.17	0.17	0.20	0.18	0.20	0.17	0.22	NS	**
	90	0.18	0.19	0.19	0.20	0.22	0.22	0.20	0.21	***	NS
18/1/2001	20	0.04	0.11	0.03	0.12	0.05	0.17	0.06	0.16	NS	***
	30	0.10	0.15	0.10	0.17	0.10	0.20	0.12	0.20	NS	***
	50	0.15	0.17	0.15	0.18	0.15	0.20	0.16	0.21	NS	***
	70	0.14	0.16	0.15	0.19	0.16	0.20	0.17	0.21	*	**
	90	0.15	0.16	0.16	0.19	0.19	0.21	0.18	0.20	***	NS
24/1/2001	20	0.03	0.13	0.03	0.18	0.05	0.19	0.06	0.20	NS	***
	30	0.10	0.17	0.09	0.21	0.11	0.22	0.12	0.23	NS	***
	50	0.16	0.19	0.15	0.21	0.16	0.21	0.17	0.23	NS	**
	70	0.15	0.18	0.15	0.20	0.16	0.20	0.17	0.23	NS	**
	90	0.14	0.16	0.15	0.19	0.19	0.20	0.17	0.21	***	**
1/2/2001	20	0.04	0.16	0.04	0.15	0.08	0.20	0.08	0.20	*	***
	30	0.10	0.19	0.09	0.18	0.13	0.22	0.13	0.23	*	***
	50	0.16	0.20	0.15	0.19	0.17	0.22	0.17	0.23	NS	***
	70	0.15	0.18	0.15	0.18	0.18	0.22	0.17	0.22	*	***
	90	0.15	0.16	0.15	0.17	0.20	0.21	0.17	0.20	***	***
8/2/2001	20	0.05	0.13	0.05	0.15	0.10	0.20	0.09	0.19	***	***
	30	0.10	0.18	0.10	0.18	0.13	0.22	0.13	0.22	**	***
	50	0.18	0.19	0.15	0.18	0.17	0.22	0.17	0.22	NS	***
	70	0.15	0.17	0.15	0.18	0.17	0.21	0.17	0.21	NS	***
	90	0.15	0.15	0.14	0.17	0.19	0.20	0.17	0.19	***	***
14/2/2001	20	0.03	0.11	0.04	0.12	0.09	0.18	0.08	0.16	***	***
	30	0.09	0.16	0.10	0.16	0.13	0.21	0.13	0.20	**	***
	50	0.16	0.17	0.15	0.17	0.17	0.20	0.17	0.21	NS	**
	70	0.15	0.16	0.15	0.16	0.17	0.19	0.16	0.20	**	***
	90	0.14	0.14	0.12	0.14	0.18	0.19	0.16	0.18	***	***
23/2/2001	20	0.02	0.14	0.04	0.15	0.08	0.20	0.08	0.17	***	**
	30	0.08	0.18	0.09	0.18	0.13	0.23	0.13	0.21	***	**
	50	0.16	0.18	0.15	0.18	0.16	0.22	0.17	0.22	**	**
	70	0.14	0.17	0.14	0.17	0.16	0.21	0.16	0.21	**	**
	90	0.13	0.15	0.11	0.13	0.16	0.19	0.15	0.17	***	**
1/3/2001	20	0.03	0.14	0.04	0.13	0.08	0.19	0.08	0.16	***	***
	30	0.08	0.18	0.09	0.17	0.13	0.21	0.13	0.20	***	**
	50	0.15	0.19	0.14	0.18	0.17	0.22	0.17	0.21	**	**
	70	0.14	0.17	0.14	0.16	0.16	0.21	0.16	0.20	**	**
	90	0.12	0.14	0.11	0.13	0.16	0.18	0.15	0.17	***	**
22/3/2001	20	0.08	0.15	0.10	0.15	0.14	0.19	0.12	0.17	***	**
	30	0.10	0.18	0.12	0.18	0.16	0.22	0.15	0.20	***	**
	50	0.16	0.19	0.15	0.18	0.18	0.22	0.18	0.21	***	**
	70	0.14	0.17	0.14	0.17	0.16	0.21	0.17	0.20	***	**
	90	0.12	0.14	0.11	0.13	0.17	0.19	0.16	0.17	***	**

With regards to depth differences were found at 20 cm on the 10/12/2000 in the tape line and this trend continued until the end of the season. In early January differences were apparent for all depths next to the tape accept the 90 cm reading, which showed differences on the 24/1/2001. Differences in soil water content next to the plant line were inconsistent until later in the season. Differences were most commonly observed in the 20 cm region and from the first of February these difference remained until the last reading on the 22/3/2001. The background shading represents the pattern of drying down the profile over time. The 50% treatment appeared to dry faster than other treatments in both the plant line and next to the tape. All treatments dried significantly between the 20/12/2000 and the 4/1/2001 and tended not to regain this used water for the rest of the season.

4.2.3. Day Change.

On the 23/2/2001 the profile water content was measured in the morning (after the previous days irrigation) and again in the afternoon. The experiment was not irrigated between these readings. Significant differences were found at all depths (using paired t-tests) , particularly for measurements made in the tape line (Table 4.9), except for the 70 cm depth in the plant line. The difference in profile water content during the day was 1.1 and 14.5 mm for the plant line and tape readings respectively.

Table 4.9. Differences between morning and afternoon readings from 64 neutron moisture meter access tubes taken on the 23/2/2001. Profile water content in mm, depth readings in cm^3/cm^3 at 'Bellevue' Warren.

Position	Depth (cm)	7:00 AM	5:00 PM	Difference	Standard Error	Prob < t
Plant	20	0.056	0.054	-0.002	0.001	0.018
	30	0.110	0.109	-0.001	0.001	0.008
	50	0.160	0.159	-0.001	0.000	0.005
	70	0.151	0.151	0.000	0.001	0.590
	90	0.138	0.135	-0.003	0.001	0.000
Profile water content		106	105	-1	0	0
Tape	20	0.165	0.140	-0.025	0.003	0.000
	30	0.199	0.177	-0.022	0.003	0.000
	50	0.201	0.190	-0.012	0.002	0.000
	70	0.186	0.177	-0.009	0.002	0.000
	90	0.160	0.154	-0.006	0.003	0.002
Profile water content		165	150	-14	1	0

4.2.4. Water Balance

Both the predicted and measured profile water contents declined in all treatments between the first 2 measurement times on 23/11/2000 and 10/12/2000 (Figure 4.17). A decrease in profile water content was then measured in all treatments between 13/12/2000 and 20/12/2000, but not predicted. A further decline in soil water content was then both measured and predicted for all treatments from 20/12/2000 until 4/1/2001. The balance between predicted and measured profile water contents then varied between the treatments in a similar pattern to that observed in the 1999/2000 season. Generally, the profile water content of the 125% treatment predicted to change more than was measured. Conversely, the profile water content of the 50% treatment generally changed less than predicted.

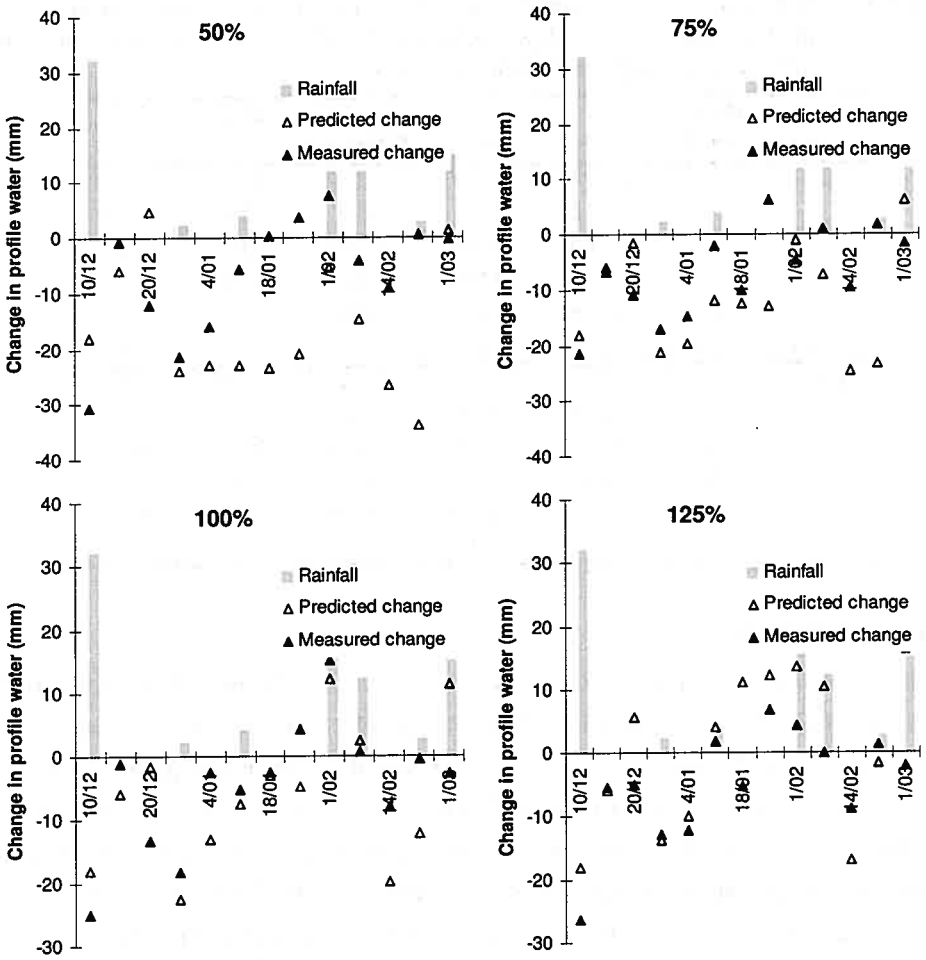


Figure 4.17. Comparison between changes between profile water content measured from one Neutron Moisture Meter reading to the next and changes predicted from water applied, rainfall and crop evapotranspiration predicted according FAO 56 (Allen *et al.*, 1998). Measurements recorded at 'Bellevue', Warren 2000/2001 season.

The correlations between the measured and the predicted changes (Figure 4.18) were r^2=0.612 for the 125% treatment and declined to 0.457 for the 100% treatment and further declined to less than 0.10 for the remaining two treatments.

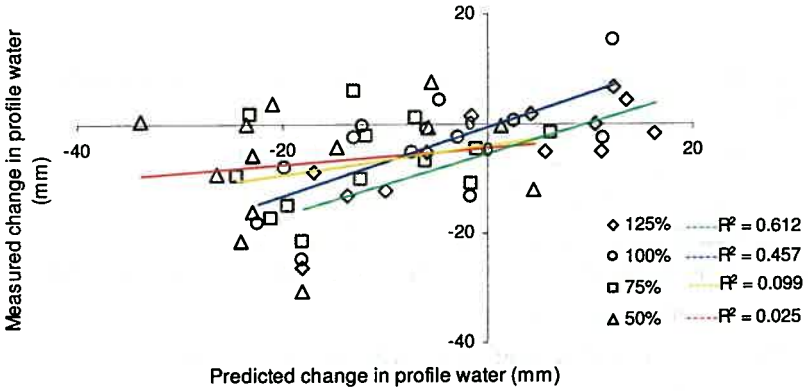


Figure 4.18. Measured against predicted changes in profile water content. Measured changes determined by the change in profile water content from one Neutron Moisture Meter reading to the next and changes predicted from water applied, rainfall and crop evapotranspiration predicted according FAO 56 (Allen *et al.*, 1998). Measurements recorded at 'Bellevue', Warren 2000/2001 season.

4.2.5. Plant Establishment

As with the 1999/2000 seasons plant densities counted in each treatment ranged from 1 to 13 plants/m. The average density in each treatment was also variable. Densities calculated were 5.6, 5.8, 5.5 and 7.2 plants/m for the 50%, 75%, 100% and 125% treatments respectively. The variable nature of the plant stand was reflected in the standard deviation of 3 plants/m that was recorded for all four treatments.

4.2.6. Canopy Temperature and Leaf Water Potential

The range of canopy temperatures between the 4 treatments was less than 1°C for all 3 measurement times (Table 4.10). These differences were significant on 30/12/2000 and 21/1/2001. However, this

data is difficult to interpret since the differences between the temperatures between the 4 blocks were greater than the differences between the treatments. For readings taken on 30/12/2000 the average temperature for Block 1 was 26.5°C, Block 2 was 28.5°C, Block 3 was 30.1°C and Block 4 was 29.0°C. This gives a range of 3.6°C which is five times greater than the range of treatment temperatures.

Table 4.10. Canopy temperature (°C) recorded from 7 am in drip irrigation experiment at 'Bellevue', Warren.

Date	50%	75%	100%	125%	l.s.d.
30/12/2000	28.1	28.3	27.7	28.4	0.3
5/1/2001	27.6	27.8	27.7	27.6	ns
21/1/2001	34.1	34.1	33.7	33.5	0.4

Leaf water potential differentiated between the treatments on two of the four measurement times (Table 4.11). The 50% treatment had larger leaf water potential than the remaining three treatments on 11/12/2000. The 125% treatment had significantly smaller leaf water potential than the 75% treatment on 31/12/2001. This was a similar trend to that recorded for canopy temperature on the same date. The leaf water potential of all treatments on 30/12/2000 and 31/12/2000 was much nearly double that recorded on 11/12/2000 and 19/12/2000.

Table 4.11. Leaf water potential (-MPa) recorded from 7 am in drip irrigation experiment at 'Bellevue', Warren.

Date	50%	75%	100%	125%	l.s.d.
11/12/2000	1.16	1.00	1.00	0.98	0.09
19/12/2000	1.15	1.20	1.20	1.09	ns
29/12/2000	2.06	2.11	1.92	1.84	ns
31/12/2000	2.06	2.11	1.86	1.80	0.30

4.2.7. Number of Nodes

The number of nodes was similar for all treatments until 1/2/2001 (Figure 4.19). The 50% and 75% treatments had fewer nodes than the 100% and 125% treatments for both measurement times in February.

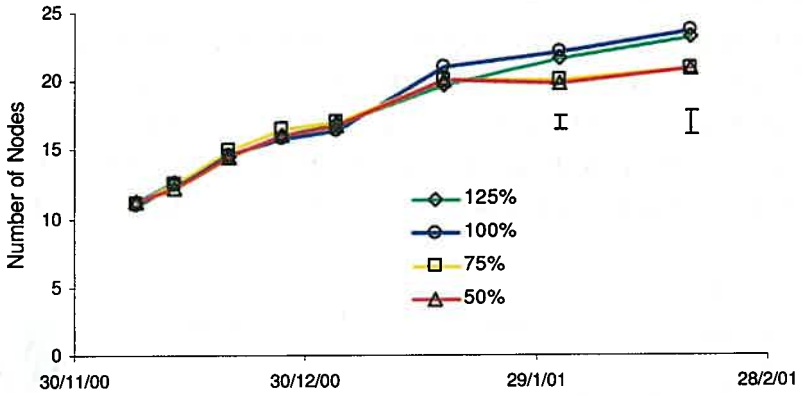


Figure 4.19. Node development at 'Bellevue', Warren. Bars are for 5% lsd.

4.2.8. Plant Height

The measured plants continued to grow for a longer time in the 100% and 125% treatments than the 50% and 75% treatments. The 125% treatment was taller than the 75% treatment on the 27/12/2000 and the 3/1/2000 (Figure 4.20). Both the 100% and the 125% treatments were taller than the 50% and 75% treatments for measurements taken in January and February.

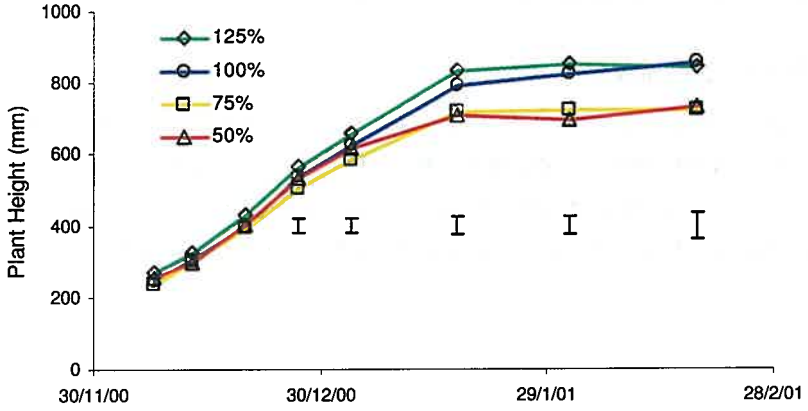


Figure 4.20. Plant height at 'Bellevue', Warren. Bars are for 5% lsd.

4.2.9. Destructive Plant Sampling

The destructive harvest showed differences between vegetative plant parts for the first harvest on 25/1/2001 (Figure 4.21). At this time, the 125% treatment had a greater weight of stems than the 50% and 100% treatments, and a greater weight of leaves than all 3 treatments receiving less water. The weight of both leaves and stems appeared to decline between harvests on 25/1/2001 and 15/2/2001 when all 4 treatments had similar weights of all 5 plant components harvested.

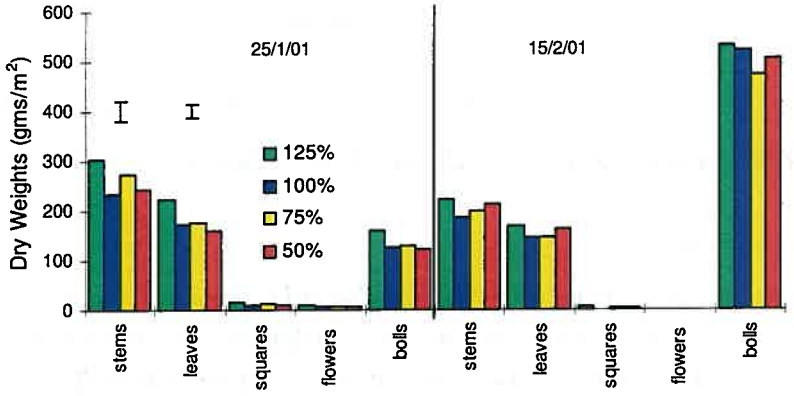


Figure 4.21. Dry weights of plant components on 2 separate destructive harvests (25/1/2001 and 15/2/2001) at 'Bellevue', Warren. Bars are for 5% lsd.

4.2.10. Fruiting Structures

Squares developed at similar rates in all treatments until the 3/1/2001 when the 125% treatment had significantly more squares than the 75% and 50% treatments (Figure 4.22). On the 17/1/2001 the 50% treatment had significantly fewer squares than other treatments while on the 1/2/2001 the 50% and 75% treatments had significantly fewer squares than the 100% and 125% treatments.

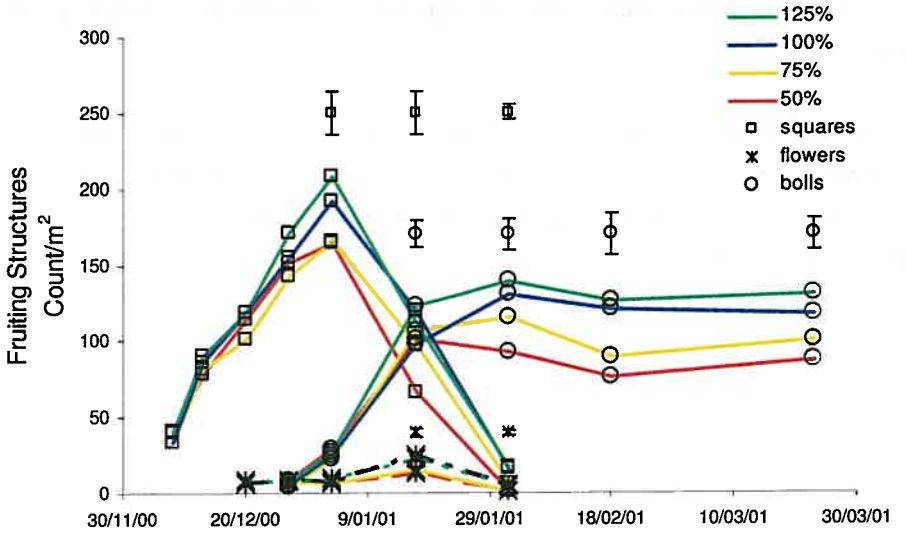


Figure 4.22. Fruiting structures recorded on drip irrigation experiment at 'Bellevue', Warren. Bars are for 5% lsd.

Similar numbers of flowers were recorded on all treatments except on the 17/1/2001 and 1/2/2001 when the 100% and 125% treatments had greater numbers of flowers than the 50% and 75 % treatments (Figure 4.22).

The number of flowers recorded is smaller than all other numbers as flowers are only short lived, existing on the plant for about two days, as a consequence flowers that appear between readings are not recorded.

Bolls appeared to initially develop at a faster rate on the 50% treatment, which had more bolls than the 75% and 100% treatments on 27/12/2000 (Figure 4.22). This trend was not evident on 3/1/2001 where there were no significant differences between the treatments.

As the season progressed the treatments receiving more water began to accumulate more bolls than the treatments receiving less water. The 125% treatment had a greater number of bolls than 50%, 75% and 100% on 17/1/2001. Both the 100% and 125% treatments had more bolls than the 50%

treatment on 1/2/2001. These two treatments had more bolls than the 50% and 75% treatments on 18/2/2001 and 28/3/2001.

Differences became apparent in the growth of the plants in mid January. While it was easy to differentiate between treatments receiving adequate water and those that were under-irrigated, it was hard to differentiate between the 50% and 75% treatments and similar for the 100% and 125% treatments as shown in Plate 4.2.

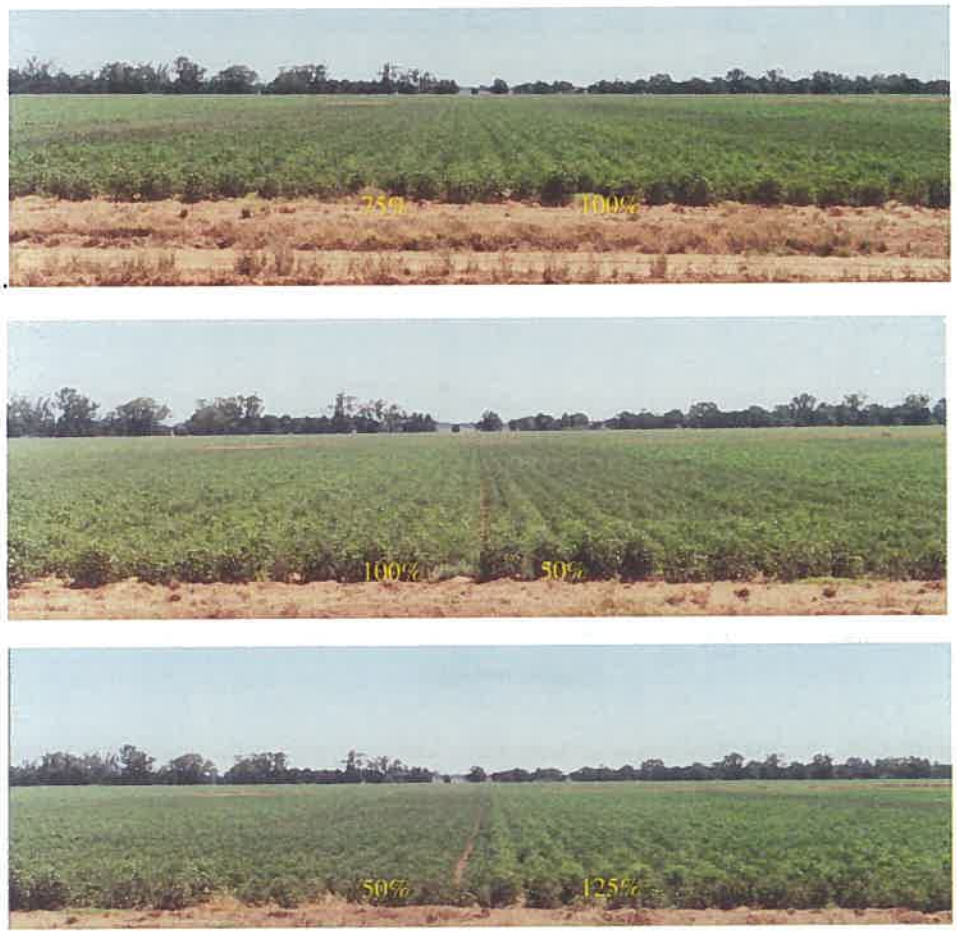


Plate 4.2 Photos of the experimental area, March 2001 at 'Bellevue', Warren.
Top: 75% treatment on right, 100% treatment on left.
Middle: 100% treatment on left, 50% treatment on right.
Bottom: 50% treatment on left, 125% treatment on right.

4.2.11. Yield

The 100% treatment yielded significantly more than the 50% treatment (Figure 4.23). There was no significant difference between the yield of 75% and 125% treatments neither was there between the 100% and 125% treatments. An aerial yield map and a yield map generated from a cotton picker is given in Appendix 5.

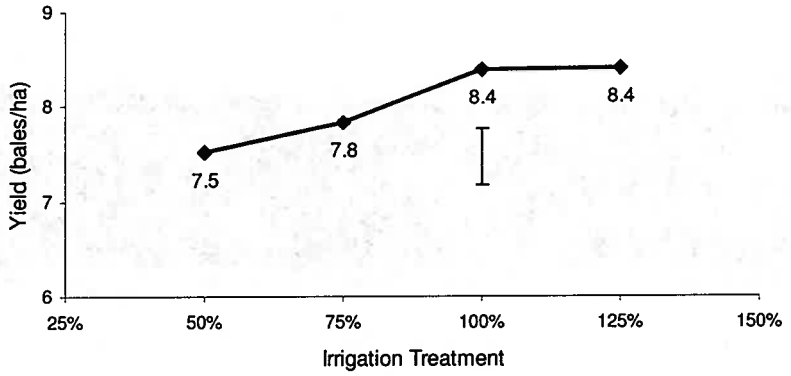


Figure 4.23. Cotton yield measured from picker harvested weights (assuming 38% turnout and 227 kg/bale) from 'Bellevue', Warren, March 2001. Bar is for 5% lsd for cotton yield

The decrease in water applied to the 50% treatment was far greater than the decrease in yield, so irrigation efficiency of the 50% treatment was greater than the remaining treatments (Table 4.12). Irrigation efficiency then declined with increasing irrigation water application.

Table 4.12 Irrigation-water use efficiency (bales/Ml) at 'Bellevue', Warren in the 2000/2001 season.

	50%	75%	100%	125%	lsd
Irrigation-water use efficiency	1.61	1.48	1.38	1.20	0.13

4.2.12. Cotton Quality

Most measured cotton quality characteristics showed no significant differences. Reflectance measurements showed the 100% (75.8 Rd) and 125% (76.0 Rd) treatments to have a greater reflectance than the 50% (74.6 Rd) and 75% (75.1 Rd) treatments. Extension measurements the 50% treatment (7.0%) showed greater extension capabilities (percentage of fibre length) than the 100% (6.6%) and 125% (6.3%) treatments.

The 2000/2001 crop was classed commercially as White Middling (31) grade and received no discounts.

4.3 Partial budget

A partial budget was calculated based on cost of water at $30 per megalitre using the average yield and water use from both seasons. Quality deductions were not taken into consideration. The 100% treatment had the highest net return (Table 4.13) both per megalitre and per hectare while the 50% treatment had the lowest. An increase in the cost of water to $200 per megalitre would have the 100% returning the highest prices per hectare and per megalitre ($479 and $91 respectively) and the 125% returning the lowest for both parameters, $204 and $33 respectively.

Table 4.13 Partial budget for each treatment. Irrigation water was assumed to be $30 per megalitre. All values are $/ha except for net return per megalitre.

Treatment	Average yield	Gross return @450/bale	Variable costs	net return ($/ha)	net return ($/Ml)
50%	6.8	3060	2215	845	229
75%	7.5	3375	2242	1133	249
100%	8.1	3645	2266	1379	261
125%	7.9	3555	2294	1261	203

5 Discussion

The following discussion will follow the following headings:

- Discussions of the relationship between yield and applied water
  - use of stored soil water.
  - crop physiological responses.
- Water use efficiency.
- Influence of the narrow wetted pattern.
- Irrigation scheduling.
- Economics.

5.1 Relationship between yield and applied water

In the two seasons over which the experiment was conducted there was a large difference between rainfall and evapotranspiration (ET). The 1999/2000 season was a wetter year than 2000/2001, which required a larger use of irrigation water. Despite these climatic differences, the 100% treatment achieved the highest yield in both seasons. Less yield was measured in each of the other treatments (with the exception of the 125% treatment in the 2000/2001 season), with the lowest yields in both seasons being recorded in the 50% treatment. Whilst a lower yields were recorded for the 50% treatment, these were disproportionate to the amount of water saved, with 78% and 89% of the yield obtained using 60% and 77% of the water applied to the 100% treatment for the 1999/2000 and 2000/2001 seasons respectively. These results suggest that the reasons for this disproportional difference could have occurred as a result of either greater utilisation of water stored in the profile and/or as a result of physiological changes in the plant.

5.1.1. Use of stored soil moisture

Neutron moisture meter (NMM) access tubes place in the plant line did not detect the same changes in soil water content as those located next to the tape. This led us to believe that there was a relatively narrow wetting pattern of less than 35 cm radius associated with the drip tape. This is consistent with the findings of Battam et al (2000a) and with the sphere of measurement of the NMM of about 15 cm radius (Charlesworth 2000). Regardless of this narrow wetted pattern changes in soil water content were observed in the plant line over both seasons and these changes were particularly rapid after a rainfall event.

We found that the area outside the zone wet by the irrigation proved to be important for the crop because it stored water that subsequently was accessed by the crop, particularly the 50% treatment, when shortfalls in irrigation were experienced. The slower decline in plant line profile water content in the 75% treatment than the 50% treatment in the1999/2000 season shows that water was extracted more rapidly from this zone in the 50% treatment. An average of 76 and 60 mm was extracted from the area outside the wetted zone over both seasons for the 50% and 100% treatments respectively. When this amount is added to the total applied water the difference between the 50% and 100% treatments is reduced to 66% and 81% for the 1999/2000 and 2000/2001 seasons. This partly explains the disproportion between yield and applied water.

We estimated that on average approximately 70 mm was stored outside the irrigated zone and made available to the cotton crop. We also saw in December 1999 that rainfall could replenish this water store.

5.1.2. Crop Physiological responses

The second probable cause for the disproportion in yield is the cotton plants response to deficit irrigation as the modern cotton plant has been derived from xerophytic origins. In ample water situations the cotton plant tends to dedicate more of its carbohydrate load into vegetative growth and, conversely, in declining water conditions the plant will concentrate its energies into ensuring the survival of the species.

In both seasons the plant height was the most sensitive of all measured plant characteristics to moisture stress. In the 1999/2000 season the differences became significant on the 29/12/1999 while the differences were significant on the 27/12/2000 in the following season however the 75% treatment was the shortest on this date.

The number of nodes was an inconsistent indicator of plant water stress. It provided an early indication of treatments effects in the 1999/2000 season when the differences became significant on the 20/12/1999. However in the following season differences were not detected until the 1/2/2001, six weeks later than the first season. The differences measured were significant but not necessarily substantial. The differences measured on the 20/12/1999 were 0.5 of a node.

Plant mapping data collected in the 1999/2000 season showed a greater number of fruit was initiated on the top of the plants in the treatments receiving the most water and, of this fruit, a higher percentage was retained. This is consistent with the growth and development of the cotton plant.

The relatively good performance of the 50% treatment may have occurred because these plants do not suffer severe water deficit stress as they are irrigated each day. Cotton can adapt to gradual development of water stress by osmotic adjustment (Hearn and Constable, 1984). As a result, the threshold leaf water potential at which various processes start to respond depends on the stress history of the crop.

The destructive harvests showed an interesting pattern of sensitivity. Samples on 25/1/2000 showed that the 125% treatment had a greater leaf weight than the remaining three treatments, but all other measures were similar for all treatments. Samples taken in the middle of February (16/2/2000 and 15/2/2001) showed no significant differences. Samples on 14/3/2001 showed that the 50% treatment had less weight of stems, leaves and bolls. This may reflect water deficit stress in this treatment as Hearn and Constable (1984) reported that water stress can promote early flowering. Although most plant parts had similar weights for the mid February sampling in both seasons, plants supported a much larger boll load in 2001 (500 g/m2) than in 2000 (250 g/m2). Some of this seasonal difference may be attributed to the late establishment in the 1999/2000 season.

Fruit counts in the 2000/2001 season found that the square production was affected by irrigation treatments on 3/1/2001 when the 50% and 75% had fewer squares than the 125% treatment. The 50% treatment then had consistently fewer bolls than the remaining treatments. The smaller boll number on the 50% treatment may be a reflection of the fewer fruiting sites available since there were fewer nodes on the 50% and 75% treatments than the 100% and 125% treatments.

The boll number rather than the boll weight had the most effect on treatment differences in final yield. Boll numbers from position 1 showed a similar contribution to the final yield. The heavier boll weights on positions 2 and 3 for the treatments receiving less water is a reflection on these plants retaining more of this fruit on the bottom of the plant and tending to fill this fruit at the expensive of further expansive growth.

The measured plant physiological responses to water treatments are consistent with what would be expected in terms of carbohydrate sink. Plants with limited water would be expected to produce less carbohydrates resulting in shorter plants with fewer nodes and shorter internode length. When the requirement of carbohydrate for boll filling is equal to carbohydrate production cotton plants will fill bolls already set in priority to new growth (Hearn, 1994). Plants with unlimited water will tend to grow vegetatively at the expense of reproductive development. These trends were observed in the experiment and probably explain the rest of the disproportion between yield and water use.

The plant line neutron moisture meter readings and the water balance also gave some indication that excess water applied to the 125% treatment was lost as deep drainage rather than being stored in the profile. This indicates that a poorly managed drip irrigation system can contribute to accessions to the water table during the growing season as well as the losses during wetting the seedbed described above.

The plant line neutron moisture meter readings and water balance could also be used to estimate the periods when the available water was insufficient to satisfy plant demand. This occurs when the predicted decline in profile water content is greater (more negative change in profile water) than the

measured decline. This was estimated to occur through much of January 2000, and to a greater extent in January 2001 when the difference was as great as 3.5 mm/day.

5.2 Water use efficiency

The decreased water use of the 50% treatment and yield that was greater than half of the 100% treatment resulted in the 50% treatment having higher water use efficiency. The 50% treatment had a water use efficiency of the of 2.24 and 1.61 bales per Ml compared with 1.36 and 1.2 bales per Ml in the 125% treatment for the 1999/2000 and 2000/2001 seasons respectively.

The treatments receiving less water made better use of water stored in the soil, so the 50% treatment had the highest irrigation efficiency in both seasons. The irrigation-water use efficiency declined with increasing irrigation water from the 50% treatment to the 125% treatment in both seasons. Tennakoon and Milroy (2000) reported irrigation-water use efficiencies in the Macquarie Valley to be 1.3 and 1.2 bales/Ml in the 1996/1997 and 1997/1998 seasons respectively, which was similar to the Australian average of 1.2 bales/Ml for both these seasons. The range of irrigation-water use efficiencies of 1.2 to 2.24 bales/Ml recorded in this experiment highlights that both the irrigation system and its management can influence how efficiently the irrigation water is used.

5.3 Influence of the narrow wetted pattern

Observations made during this experimented highlighted the short comings of having a lateral spacing of two metres. Our experience was that the drip tape was too far from the plant line at this site to allow wetting of the soil around the seed. Similar experiences have been reported elsewhere. Raine et al. (2000) reported that germination remains one of the biggest challenges for subsurface drip irrigated cotton in Australia. They found that 45% of the subsurface drip irrigated cotton in Australia relies heavily on rainfall moisture for crop establishment. In California less than 10% of surveyed growers used their buried drip systems to establish the crop (Burt and Styles 1994 quoted by Charlesworth and Muirhead, 2000).

The narrow zone wet by subsurface drip irrigation at this experimental site is also similar to that recorded elsewhere. Thorburn et al. (2000) reported that 1.65 l/hr emitters applying water for 4 hours on the surface of soil with texture ranging from sandy loam to medium clay wet an average of 22 cm radius and 46 cm depth. Charlesworth and Muirhead (2000) reported that they were able to wet the soil surface of a loam textured soil to a distance of 60 cm from buried drip tape only because of the presence of an impermeable B-horizon which minimised deep drainage. Hanson et al. (2000) observed that application of 50% more water than was being used by a tomato crop for 2 weeks resulted in the soil being wet 20 cm laterally from the tape to a depth of 60 cm. The lateral extent of wetting increased to 40 cm from the tape at 70 cm depth. These observations indicate that application of excess water from subsurface drip irrigation results in water being lost to deep drainage, and to achieve suitable subbing of the surface the water would have to be applied quicker than it can drain through the bottom of the profile.

This process can be envisaged as subsurface flood irrigation as the surface soil is only wet up after the soil around the tape is saturated. This results in the saturation of the deep soil, as occurs under surface flood irrigation, combined with greater deep drainage since the irrigation event occurs over a longer period.

The patterns of change in profile water content in the plant line and next to the drip tape provided us with useful management insights. These patterns also support the observations above that the drip irrigation system does not wet the soil in the plant line, which is 50 cm from the drip tape.

We observed that the neutron moisture meter readings next to the drip tape were a more sensitive measure of differences in profile water content between the treatments than the neutron moisture meter readings in the plant line. Significant differences between treatment profile water contents next to the tape were recorded at least one month before differences between profile water content in the plant line. The greater sensitivity of the neutron moisture meter readings next to the tape indicate that soil water should be monitored in this region to determine whether sufficient irrigation water is being applied rather than in the plant line.

Monitoring of soil water content in the plant line has helped us to understand the implications of irrigation management decisions. Measurement of soil water content in the plant line is an important component of the soil water balance. The calculated soil water balance has allowed us to observe that the water stored in the unirrigated zone can supply water rapidly to the crop. The soil water balance indicates that the rapid decline in plant line profile soil water after the rain events in December 1999 and November 2001 was similar in magnitude to crop water use predicted by the FAO 56 (Allen et al., 1998) model. This occurred because of a management decision to delay the start of irrigation until the crop had used some of the water stored in the profile from the rain. The water balance also showed that we were not applying sufficient irrigation water to satisfy crop demand in early January 2000, and again in December 2000. The plant line neutron moisture meter measurements indicate that the deficit between irrigation and evapotranspiration was satisfied by extracting water from the plant line, then extracting water next to the drip tape. These changes in profile water content indicate that we can use the soil outside the irrigated zone as a water store that can be accessed by the crop.

The irrigation-water use efficiency in both seasons was limited by the large amount of water needed to germinate the crop (70 mm in 1999/2000 and 238 mm in 2000/2001). In the 2000/2001 season the amount used to water up was more than half of the total water used in the 50% treatment while it represented 40% of the water used in the 100% treatment. The difference in water used for wetting the seedbed in the two seasons is similar to the 142 mm difference between water applied to the 50% and 100% treatments in the 2000/2001 season. It is clear that it would be better to use this extra irrigation water to obtain the greater production recorded between the 50% and 100% treatments than to use it only for crop establishment.

5.4 Irrigation Scheduling

The neutron moisture meter (NMM) access tubes placed next to the drip tape allowed small changes in the soil moisture content due to irrigation to be detected. As previously discussed the access tubes placed in the plant line didn't detect changes in soil moisture content due to the narrow wetted area.

The neutron moisture meter was able to detect the daily changes in soil water content. The measured change (averaged over all treatments) by the plant line neutron moisture meter was 1.1 mm and 14.5 mm by the neutron moisture meter readings next to the tape. Using the same ratios as used to calculate water balance this equates to a loss of 5.5 mm from the soil profile. The crop water use for the 100% treatment on the corresponding day (23/2/2001) was estimated as 7.5 mm (6.5 mm for all treatments).

Data collected from the NMM was analysed to determine number of tubes needed to monitor soil water content. The confidence interval when two access tubes are used is ±15 mm and ± 8.7 mm when 6 access tubes are used. The use of more tubes will result in greater accuracy.

Measurements of plant water stress in the 2000/2001 were disappointing in their capacity to differentiate between the treatments because changes in all treatments over time were greater than the differences between the treatments. Changes in canopy temperature showed that differences between the average temperature of the first and last block measured were always far greater than the differences between treatments. Average leaf water potential of all treatments increased by approximately 0.1 MPa/day between measurements on 19/12/2000 and 29/12/2000. Leaf water potential readings on 30/12/2000 and 31/12/2000 were close to the limit of mild stress that maximises the setting of bolls within the constraint imposed by boll load (Hearn and Constable, 1984). This indicates that the water relations at the time were close to optimum.

The leaf area index (LAI) showed significant differences on the 16/2/2000, six weeks after differences were evident in plant height. It was determined that LAI was a poor indicator of plant water status and the measurements were not repeated in the subsequent season.

In summary, there was a large variation between the time when the plant measures detected changes in plant water status. Plant height of treatments receiving less than 100% of daily water use were shorter than those receiving sufficient water from the last week in December. The number of nodes was an unreliable indicator of plant water status in this experiment. Plant canopy temperature and leaf water potential varied more for all treatments over time than between treatments. Perhaps there

is scope to refine these measures. Fruit counts showed that the 50% treatment was under stress from 3/1/2001, which is the same date that differences were observed in the profile water content next to the drip tape. Leaf Area Index was influenced little by the irrigation treatments, and the dry matter harvests are a record of what has already occurred. It was found that the usefulness of plant measures as a guide to water status for scheduling is limited by the lack of threshold values as experienced by Ayars et al. (1992).

In Australia most drip cotton growers, 57% (Raine et al., 2000), use a combination of methods to schedule irrigation that include soil moisture measurements, plant indicators and climatic data. Our findings would indicate that climatic data can be used to predict crop water use and becomes a robust scheduling tool when combined with soil water content, which can then be used to adjust the crop factor. Plant indicators were found to be less reliable because differences were inconsistent between seasons, differences took longer to become apparent than soil water content and the magnitude of the differences was relatively small.

However crop water use was underestimated in both seasons in the growth development stage. The amount under-estimated was in the order of 0.5 mm per day which equates to a relatively small change in the crop coefficient. The scheduling of irrigations with evapotranspiration data and the crop coefficient derived from Allen et al (1998) was a useful guide but must be supported by an independent measure such as soil water content.

5.5 Yield and economics.

Yield is the greatest contributor to land productivity in the Australian cotton industry (Thompson and Boyce, 2001), this also proved to be the case in this experiment. The 100% treatment yielded more than the 50% treatment in both seasons. However, the lowest yielding 50% treatment in this experiment yielded more than the average for the Macquarie Valley which was 6 bales/ha in the 1999/2000 season (Dowling, 2000) and 7.1 bales/ha in the 2000/2001 season (Dowling, 2001). The 100% treatment had the highest returns both per hectare and per megalitre. Over-irrigation of the crop resulted in lower returns because of the use of extra water without increase in yield. Under

irrigating resulted in lower returns due to lower yields. The water savings were not substantial enough to offset lower yields.

Improvements in yield could possibly be achieved by addressing two areas, firstly by improving the uniformity of the plant stand. The establishment of a satisfactory stand was difficult in both seasons with a range of 1 to 16 and 1 to 13 plants per meter being recorded in the 1999/2000 and 2000/2001 seasons respectively. This variation was reflected in the yield mapping. Improvement in the achieved plant stand could be achieved by an alternative irrigation system such as overhead sprinklers or by having a lateral spacing for the drip tape of 1 metre. The second way in which yield could be improved would be to address the under irrigation of the crop in the early part of the season. This could be achieved by the refinement in the crop factor, some of which has already been achieved as a result of the findings of this experiment.

Fibre quality measured in the 2000/2001 season displayed differences only between the extension and reflectance characteristics; however these differences proved not to be substantial and were not converted into quality differences measured on the resulting bales as no differences were found in the commercial classing (USDA standard). Differences in commercial classing in the 1999/2000 season were probably due to climatic rather than treatment effects as a result of a delayed harvest due to rain.

6 Conclusions

The amounts of irrigation predicted using the recommendations of FAO 56 (Allen at al. 1998) under supplied crop water demands in the crop development stage, however, supplied sufficient water to satisfy crop evapotranspiration in the flowering and yield formation stages in two seasons with differing temperature regimes.

Excess water applied to the 125% treatment appeared to be lost as deep drainage at this site rather than being stored in the profile.

The neutron probe is sensitive to small changes in soil water content and therefore may be a useful tool for scheduling irrigations on drip irrigated cotton.

Soil water stored outside the irrigated zone appeared to be used rapidly by the plants to satisfy shortfall between irrigation and evapotranspiration. We also saw that this soil water store was replenished by rainfall. Delaying the start of irrigation after rainfall caused a rapid decline in this soil water store under our management regime.

Under-irrigating cotton plants reduced the plant height, number of nodes, leaf area and boll number however over-irrigating did not result in a significant increase in these measured plant components.

The most responsive indicators of water available to the plant were plant height (until mid January when the crop stopped producing new nodes) and profile water content next to the tape.

We found that gradual development of water stress (by under-irrigating daily) allowed cotton plants to make osmotic adjustments that allowed the 50% treatment to yield only 17% less than the 100% treatment despite only receiving 31% less water.

Subsurface drip irrigation is an inefficient method of wetting the seedbed and establishing the crop. This is a major limitation to our aim of growing high yielding crops with as little water as possible using drip irrigation.

We found that the irrigation efficiency was limited in both seasons by the large amount of water required to germinate the crop (27% of water applied to the 100% treatment). It is clear that it would be better to use this extra irrigation water to obtain the greater production recorded between the 50% and 100% treatments than to use it only for crop establishment.

7 Recommendations

Irrigate daily based on estimated crop water use for previous day.

Place soil moisture monitoring devices next to the tape, and monitor water status in the plant line less intensively. It is important to monitor water status in the plant line up to start of irrigation, after rain, and weekly through the season until the soil dries to wilting point.

To get meaningful results from the neutron moisture meter take readings at a similar time of day. As evapotranspiration rates vary through the day, take readings at dawn and plan to irrigate on completion. This will give a reading when the soil is at its lowest water content and will have given the soil water time to equalize.

The number of neutron moisture meter access tubes and the confidence interval is listed in Table 7.1.

Table 7.1. Number of access tubes required to obtain different confidence intervals.

Tube number	Confidence interval (mm)
2	± 15
3	± 12.2
4	± 10.6
5	± 9.5
6	± 8.7

Plant height can be used to monitor cotton growth rate until mid January (peak flowering).

A method of reliably establishing cotton crops grown on subsurface drip irrigation is needed before this irrigation system can be widely used. Further research is needed on this topic

The use of water from under the plant line while ample water seems to be in existence around the tape would suggest that waterlogging may be occurring. Further research is needed on this topic.

8 References

Abdelhadi, A.W., Takeshi, H., Tanakamaru, H., Tada, A. and Tariq, M.A. 2000. Estimation of crop water requirements in arid region using Penman-Monteith equation with derived crop coefficients: a case study on Acala cotton in Sudan Gezira irrigated scheme. Agricultural Water Management. 45 203-214

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998 Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome.

Anac, M.S., Ali Ul, M., Tuzel, I.H., Anac, D., Okur, B. and Hakerlerler, H. 1999. Optimum irrigation schedules for cotton under deficit irrigation schedules. In: Crop yield response to deficit irrigation. Eds. C. Kirda, P. Moutonnet, C. Hera and D.R. Nielson. Kulwer Academic Publishers.

Anderson, A.N., McKenzie, D.C. and Friend, J.J. (eds.). 1999. SOILPAK. For dryland farmers on the red soil of Central Western NSW. NSW Agriculture, Orange.

Anon. 2000. Cable free moisture monitoring. The Australian Cotton Grower. 21(1):83

Anon. 1998. Drip irrigation proves its worth. The Australian Cotton Grower. 19(2):74

Anon. 1996. Cotton agronomy resource manual. New England Institute of TAFE. NSW.

Anon. 1988. Drip irrigation set to boost yield. The Australian Cotton Grower. 9(1):61

Bannister, B. 1988. Drip irrigation to lift yield and cut costs. The Australian Cottongrower. 9(2):53.

Ayars, J.E., Phene, C.J., Hutchmaker, R.B., Cardon, G.E. and Clark, D.A. 1992. IRRIGATION SCHEDULING: Techniques for irrigation scheduling of subsurface drip irrigation. Subsurface Drip Irrigation Theory Practices and Applications CATI Publication Number 92 1001 pp 105-118

Battam, M. and Sutton, B. 2000.Water surfacing from buried drip irrigation systems. The Australian Cottongrower. 21(3):46.

Battam, M., Hulme, P. and Sutton, B. 2000a. Soil water movement beneath drip irrigated cotton. The Australian Cottongrower. 21(3):29

Battam, M.A., Boughton, D.G. and Sutton, B.G. 2000b. A simple technique for use in the design of drip irrigation systems. In "Water - essential for life" Proceedings of the Irrigation Association of Australia National Conference. pp. 261-268

Bird, T.L., Willis, T.M. and Melville, G. (1996) Subsoil hydraulic conductivity estimates for the Lower Macquarie Valley. Australian Journal of Soil Research. 34:213-218.

Borthwick, C..M. 2000. The effects of drip and furrow irrigation on cotton plant root growth and development in Australian red soils. Undergraduate Thesis. University of Sydney.

Burt, C. M. and Styles, S.W. 1994. Drip micro-irrigation for trees vines and row crops. Irrigation Training and Research Centre, California Polytechnic State University, San Luis Obispo, California.

Carmi, A., Plaut, Z., Heuer, B., and Grava, A. 1992. Establishment of shallow and restricted root systems in cotton and its impact on plant response to irrigation. Irrigation Science 13: 87-91

Charlesworth, P.B. 2000.Soil Water Monitoring. Irrigation Insights No. 1. CSIRO Land and Water Australia, Camberra.

Charlesworth, P.B., and Muirhead, W. 2000. Facing the SDI crop establishment problem. Irrigation Australia 2000 Conference Proceedings. (ed G.J. Connellan). Irrigation Association of Australia. pp. 276-286.

Cockcroft, B. and Martin, F.M., 1981. Irrigation. In: J.M. Oades, D.G. Lewis, and K. Norrish (eds.), Red-brown earths of Australia. CSIRO, Adelaide, South Australia. pp.133-147

Coelho, E. F. and Or, D. 1996. Flow and uptake patterns affecting soil water sensor placement for drip irrigation management. Transactions of the ASAE. 39: 6, 2007-2016

Constable, G.A., and Hodgson, A.S. 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil. 3. Yield and quality of four cultivars. Irrigation Science. 11:149-153.

Constable, G. 1991. Mapping the production and survival of fruit on field grown cotton. Agronomy Journal. 83:374-378

Constable G.A. and Gleeson A.C. 1977. Growth and distribution of dry matter in cotton. Australian Journal of Agricultural Research. 28: 249-56

Craze, B. and Hamilton, C.J. 1991. Soil Physical Properties. In: Soils: their properties and management. Soil Conservation Service of NSW. (Eds Charman, P.E.V. and Murphy, B.W.) pp 147-164

Creighton, G., Cross, N., Elton. K., Elliott, S., Evans, L., OReilly, T., Robbins, M., Rolfe, C., Sanderson, A. and Smith, P. 1999. Evaluating your drip irrigation system. Introduction to Irrigation Management. Waterwise on the farm. NSW Agriculture.

Cull, P.O., Hearn, A.B., and Smith, R.C.G. 1981a. Irrigation scheduling of cotton in a climate with uncertain rainfall. I. Crop water requirements and response to irrigation. Irrigation Science. 2:127-140.

Cull, P.O., Smith, R.C.G., and McCaffery, K. 1981b. Irrigation scheduling of cotton in a climate with uncertain rainfall. II. Development and application of a model for irrigation scheduling. Irrigation Science. 2:141-154.

Dargie, J.D. 1999. Preface. In: Crop yield response to deficit irrigation. Eds. C. Kirda, P. Moutonnet, C. Hera and D.R. Nielson. Kulwer Academic Publishers. Pp. vii

da Roza G.D., Hearn, A.B. and Fleming, P.M. (199?). Calibration of the water balance model for cotton in the Namoi Valley, New South Wales: 1. The aerodynamic component of the combination equation. Unpublished report

Dearden, J. 2000. Pitfalls of soil water monitoring: from dam building to damned drippers. In "Soil Water monitoring" Irrigation Insights No. 1. (Ed Phillip Charlesworth). pp 56-60

de Koch. J., de Bruyn, L.P. and Hunman, J.J. (1993). The relative sensitivity of plant water stress during the reproductive phase of upland cotton (Gossypium hirsutum L.) Irrigation Science. 14, 239-244

DeTar, W.R., Phene, C.J., and Clark, D.A. 1994 Subsurface drip Vs furrow irrigation: 4 years of continuous cotton on sandy soil. 1994 Proceedings Beltwide Cotton Conferences. San Diego, CA. pp 542-5

Doorenbos, J. and Kassam,A.H. 1979. Yield responses to water. FAO Irrigation and Drainage Paper 33, Rome.

Dowling, D. 2000. 1999 2000 Cotton Season. In: Cotton Yearbook 2000. pp 4-5

Dowling, D. 2001. 2000-01 Cotton Season. In: Cotton Yearbook 2001. pp 4-5

Elliott, M. 1995. Irrigation Farming in the Macquarie Valley. New South Wales Agriculture, Orange, NSW.

Fangmeier, D.D., Garrot, D.J.Jr. Husman, S.H. and Perez, J. 1989. Cotton water stress under trickle irrigation. Transactions of the ASAE. Vol. 32(6) 1955-59

Greacen, E.L., 1981. Physical properties and water relations. In: J.M. Oades, D.G. Lewis, and K. Norrish (eds.), Red-brown earths of Australia. CSIRO, Adelaide, South Australia. pp. 83-86

Grimes, D. W. Miller, R. J. Schweers, V. H. Smith, R. B. and Wiley, P. L. 1972. Soil strength modification of root development and soil water extraction. California Agriculture. 26: 11, 12-14.

Hall, D.J.M., McKenzie, D.C., MacLeod, D.A., and Barrett, A., 1994a. Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. I. Soil physical and chemical properties. Soil Tillage Res., 28: 253-270.

Hall, D.J.M., McKenzie, D.C., MacLeod, D.A., and Toole, I.D., 1994b. Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. II. Soil-water relations. Soil & Tillage Res., 28: 271-285.

Hall, D.J.M., McKenzie, D.C., MacLeod, D.A., and Toole, I.D. 1994c. Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. III. Crop production and profitability. Soil & Tillage Research.28: 287-300.

Hanks, R.J. and Ashcroft, G.L. 1980 Applied Soil Physics: soil water and temperature applications. Springer-Verlag, New York.

Hanson, B.R. and May, D.M. 2000. Response of processing tomatoes to drip irrigation under saline, shallow groundwater conditions. Irrigation Association of Australia. pp. 277-286.

Hearn, A.B. 2000. The science of water balance: Why do we need to know? In: Proceedings of the 10th Australian Cotton Conference. Brisbane.

Hearn, A.B. 1994. The principles of cotton water relations and their application in management. Challenging the Future: Proceedings of the World Cotton Research Conference-1, Brisbane Australia, February 14-17, 1994.

Hearn, A.B. 1979 Water relationships in cotton. Outlook on Agriculture 10, 159-166

Hearn, A.B. and Constable, G.A. 1984. 'Cotton'. In: P.R. Goldsworthy and N.M. Fisher (eds) The Physiology of Tropical Food Crops. John Wiley & Sons Ltd. Chichester. pp. 495-527

Hearn, B., Cameron, J. and Jackson, B. 1997. Water use efficiency: If you don't measure it you can't manage it. The Australian Cottongrower. 18(6):88-94

Hsiao, T.C., Fereres., Acevedo, E. and Henderson, D.W. 1976. F. Water stress and dynamics of growth and yield of crop plants. In: Water and Plant Life. Problems and modern approaches. Eds. O.L. Lange, L. Klappen and E.-D. Schulze. Springer-Verlag, New York.

Henggeler, S. 1999. Evaluation of Drip Irrigation As an Alternative to Furrow Irrigation on Grey Cracking Clays. AUSCOTT LTD - NAMOI VALLEY OPERATIONS. Unpublished report.

Hillel, D. 1971. Soil and Water: Physical Properties and Processes. Academic Press, New York.

Hillel, D. 1980. Applications of Soil Physics. Academic Press, New York.

Hulme, P.J. 1998. Irrigation management of cotton under drip in the Macquarie Valley 1997/98 season. Report for MBDC project I7020: Complimenting micro-irrigation technology with improved irrigation management based on crop and soil parameters.

Hulme, P.J. and Elliot, M. 1995. Formation and distribution of soils. In "Irrigation farming in the Macquarie Valley" (Ed. M. Eliot). NSW Agriculture, Trangie.

Hulme, P.J. and OBrien, B.F. 2000a. Managing subsurface drip irrigation in hardsetting red soil - implications of a small wetted area. In "Water - essential for life" Proceedings of the Irrigation Association of Australia National Conference. pp. 385-390

Hulme, P.J. and OBrien, B.F. 2000b. Investigation of irrigation management of drip irrigated cotton soil to maximise yield. In The Proceedings of the 10th Australian Cotton Conference. Brisbane 2000.

Hulme, P.J., McKenzie, D.C., Abbott, T.S., and MacLeod, D.A., 1991. Changes in the physical properties of a Vertosol following an irrigation of cotton as influenced by the previous crop. Australian Journal of Soil Research. 29:425-442.

Hulugalle, N.R., Friend, J.J. and Kelly, R. 2000. Seasonal changes in quality of hardsetting red soils under trickle and furrow irrigated cotton in the Macquarie Valley of New South Wales. In "Water - essential for life" Proceedings of the Irrigation Association of Australia National Conference. pp. 525-529

Hulugalle, N.R., Friend, J.J. and Kelly, R. 2001 Some physical and chemical properties of hardsetting alfisols can be affected by trickle irrigation. Unpublished

Hutchmaker, R.B., Phene, C.J., Davis, K.R., Pflaum, T., Peters, M.S., Vail, S.S., Bravo, A.D., Hawk, C.A., Clark, D., Ballard, D.A., Hudson, N., Kerby, T.A., and Keeley, M. 1994. Acala and pima cotton water relations and nutrient management under subsurface drip irrigation. In "1994 Proceedings beltwide cotton conferences" Vol. 3 pp. 1255-1751

Hutchmaker, R.B., Phene, C.J., Davis, K.R., Vail, S.S., Kerby, T.A., Peters, M., Hawk, C.A., Keely, M., Clark, D.A., Ballard, D. and Hudson, N. 1995. Evaporation, fertility management for subsurface drip Acala and Pima cotton. In: 'Proceedings of 5th International Drip/Trickle Irrigation Congress, St Joseph, Michigan. (Ed F.R. Lamm). ASAE. pp. 147-154.

Lange, O.L., Kappen, L. and Shulze, E.-D. 1976. Water and Plant Life. Problems and modern approaches. Springer-Verlag, New York.

McKenzie, D.C., Hucker, K.W., Morthorpe, L.J., and Baker, P.J. 1990. Field calibration of a neutron-gamma probe in three agriculturally important soils of the Lower Macquarie valley. Australian Journal of Experimental Agricultural Agriculture. 30:115-122.

McKenzie, D.C. (ed.). 1998. SOILpak (3rd ed.). NSW Agriculture, Orange. McKenzie, N.J., 1992. Soils of the Lower Macquarie Valley, New South Wales.CSIRO Division of Soils Divisional Report No. 117. CSIRO, Canberra. 73 pp.

McKenzie, N.J. 1992. Soils of the Lower Macquarie Valley, New South Wales. CSIRO Division of Soils Divisional Report No. 117. CSIRO, Canberra. 73 pp.

Meron, M., Grimes, D.W., Phene, C.J. and Davis, K.R. 1987. Pressure chamber procedures for leaf water potential measurements of cotton. Irrigation Science. 8: 215-222

Meyer W S 1999. Standard Reference evaporation Calculation for Inland, South Eastern Australia. Technical Report 35/98 17 September 1999, CSIRO Land & Water.

Meyer, W.S. and Ritchie, J.T. 1980. Water status of cotton as related to taproot length. Agronomy Journal 72: 577-580

Moreshet, S., Fuchs, M., Cohen, Y., Cohen, Y., and Langensiepen, M. 1996. Agroclimatology: Water transport characteristics of cotton as affected by drip irrigation layout. Agronomy Journal. 88:717-722

Muldoon, D., Hickey, M. and Hoogers, R. 2000. Rooting depth of irrigated rockmelons on clay soils. In "Soil Water monitoring" Irrigation Insights No. 1. (Ed Phillip Charlesworth). pp 51-53

Mullins, C.E., MacLeod, D.A., Northcote, K.H., Tisdall, J.M., and Young, I.M. 1990. Hardsetting soils: behaviour, occurrence and management. Advances in Soil Science. 11: 37-108.

Mullins, G. L. Schwab, G. J. and Burmester, C. H. 1997. Growth and nutrient uptake by cotton roots under field conditions. 1997 Proceedings Beltwide Cotton Conferences, New Orleans, LA, USA, January 6-10, 1997: Volume 1. National Cotton Council, Memphis, USA: 575.

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H. and Bettenay, E. 1975. A description of Australian Soils. CSIRO. Australia.

O'Connell, B. 1998. Drip system delivers for Tandou. The Australian Cottongrower. 19(3):40-41.

Passioura, J. B. and Stirzaker, R. J. 1993. Feedforward responses of plants to physically inhospitable soils. International crop science 1. Crop Science Society of America. 715-719

Phene, C.J., Hutchmaker, R.B. and Davis, K.R. 1992. Subsurface drip irrigation: cotton does not need to be a high water user. Proceedings of the Beltwide Cotton Conference, 1:489-493

Plaut, Z., Carmi, A., and Grava, A. 1996. Cotton root and shoot responses to subsurface drip irrigation and partial wetting of the upper soil profile. Irrigation Science. (1996) 16: 107-113

Prieto, D. and Angueira, C. 1999. Water stress effect on different stages for cotton and its influence on yield reduction. Crop Yield Response to Deficit Irrigation. Eds. Kirda, Moutonnet, Hera and Nielson. Pp. 161.

Radin, J.W., Mauney, J.R. and Kerridge, P.C. 1989 Water uptake by cotton roots during fruit filling in relation to irrigation frequency. Crop Science. 29: 1000-1005

Raine, S.R., Foley, J.P. and Henkel, C.R. 2000. Drip irrigation in the Australian cotton industry: a scoping study. National Centre for Engineering in Agriculture Publication 179757/2, USQ, Toowoomba.

Rhone Poulenc, Prep 720 Manual.

SAS Institute Inc. 2000. JMP Version 4 Statistical Software

Schoneman, R.A. Nightengale, H.I. and Varnell, B. 1992. Field installation at Britz Farms Subsurface Drip Irrigation; Theory Practices and Applications. ATI Publication Number 92 1001 pp 179-181

Shani, U., Xue, S., Gordin-Katz, R., and Warrick, A.W. 1996. Soil-Limiting Flow from Subsurface Emitters. I: Pressure Measurements. Journal of Irrigation and Drainage Engineering. September/October 1996

Scholander, P.F., Hammel, H.T., Bradstreet, E.D. and Hemmingson, E.A. 1965. Sap pressure in vascular plants. Science. 134:1835-1838.

Schwab, G. J. Mullins, G. L. and Burmester, C. H. 2000. Growth and nutrient uptake by cotton roots under field conditions. Communications in Soil Science & Plant Analysis. 31: 1/2, 149-164. 34

Sinclair, P.J., Abbott, T.S. and Gilmour, A.R., 1992. Effects of furrow and water treatments on the absorption of water into beds of structurally unstable red-brown earths. Soil Tillage Research, 25: 245-261

Stirzaker, R. J. Passioura, J. B. and Wilms, Y. 1996. Soil structure and plant growth: impact of bulk density and biopores. Plant & Soil. 185: 1, 151-162. 42

Taylor, H.M. and Klepper, B. 1974. Water relations in cotton. 1. Root growth and water use as related to top growth and soil water content. Agronomy Journal. 66: 4, 584-588

Tennakoon, S.B. and Milroy, S.P. 2000. Evaluation of crop water use efficiency and farm level irrigation efficiency of irrigated cotton farms in northern NSW and southern Queensland. Irrigation Australia 2000 Conference, 23-25 May 2000, Melbourne.

Thompson, P. and Boyce, R. 2001. Economics of redevelopment. Proceedings of the NW IAA Annual Field Day. Narrabri. Nov 2001.

Thorburn, P.J., Cook, F.J. and Bristow, K.L. 2000. The influence of soil properties on wetting patterns from trickle emitters Irrigation Australia 2000 Conference, 23-25 May 2000, Melbourne.

Tisdall, J.M., Cockcroft, B., and Uren, N.C., 1978. The stability of soil aggregates as affected by organic materials, microbial activity and physical disruption. Australian Journal of Soil Research. 16:9-17.

T-Tape. 1996. Cotton. Publicity brochure.

Wanjura, D.F. and Mahan, J.R. 1994. Thermal environment of cotton irrigated using canopy temperature. Irrigation Science. 14: 199-205

Willis, T., and Hulme, P. 1996. Some soils leak too much when irrigated. The Australian Cottongrower. 17(5):28-30.

Willis, T.M., Black, A.S. and Meyer, W.S. 1997. Estimates of deep percolation beneath cotton in the Macquarie Valley. Irrigation Science. 17: 141-150

Willis, T.M., Hall, D.J.M., McKenzie, D.C. and Barchia, I. 1999. Soybean yield as affected by crop rotations, deep tillage and irrigation layout on a hardsetting Alfisol. Soil and Tillage Research. 44: 151-164

Wuertz, H. and Tollefson, S. 1992. Subsurface drip irrigation on Sundance Farms Ltd. Coolidge, Arizona. In "Subsurface drip irrigation: theory practices and application." CATI Publication number 921001. USDA Agricultural Research Service.

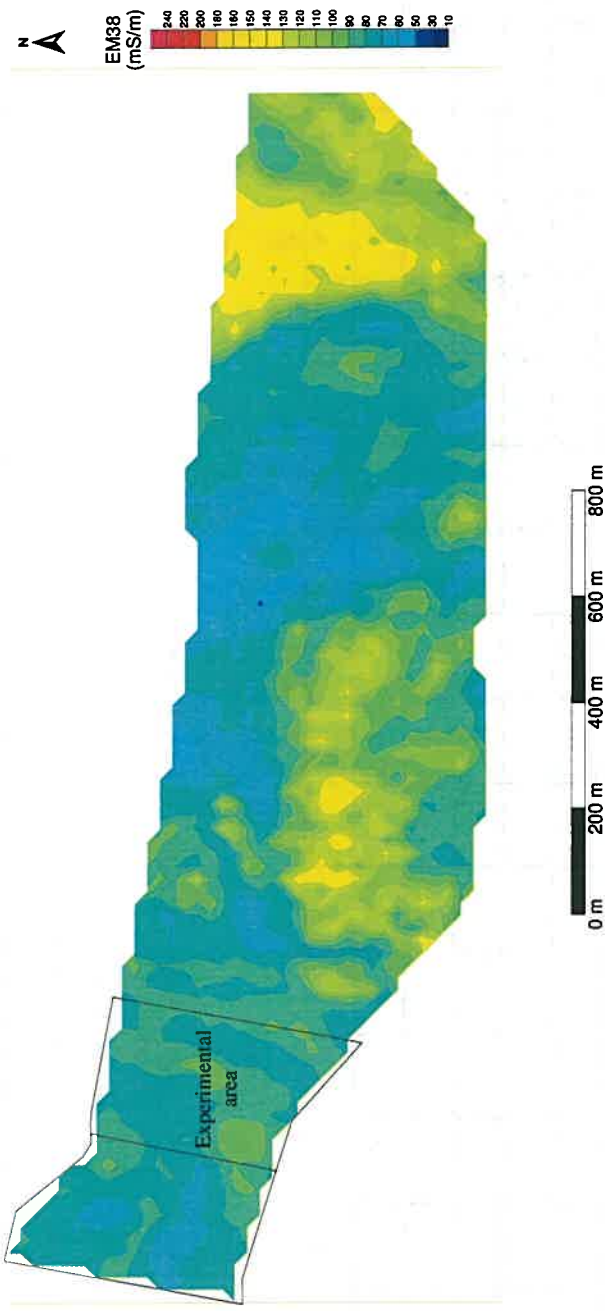
Appendices

Appendix 1 Soil moisture metering devices. Source: Charlesworth (2000).

Measurement System	Mode of Measurement	Generic Name	Commercial Products
Water potential			
Porous media:	measures soil moisture potential	Tensiometers	SoilSpec®, Terra Tech®, JetFill®, Irrometer®
		Gypsum blocks	GBLite®, Watermark®
		Combination (VSW sensors embedded in a porous material)	Equitensiometer, CampbellScientific 229
Wetting-front:	(1):measures the electrical resistance of a porous materal,		Wetting Depth Probe, Cut Off Sensor
	(2): detection of flow distortion around a burried object		Fullstop®
Volumetric soil water content (VSW)			
Soil dielectric:	measures electromagnetic properties of the soil water media	Time domain reflectometry (TDR)	Trase® TDR, Tektronix 1502 TDR, Campbell Scientific TDR100, Campbell 615, Aquaflex®, Gro-Point®
		Frequency domain reflectometry (FDR) capacitance type probes	EnviroSCAN®, Diviner 2000®, C-Probe®, Gopher®, Buddy®, Aquaterr®, Thetaprobe®, Netafim Soil Moisture Data Collector
Neutron moderation:	measures fast moving neutrons that are slowed by colliding with hydrogen particles (hydrogen is present in water).	Neutron moisture meter (NMM)	Campbell Pacific Nuclear 503® NMM
Heat dissipation:	measures energy used to heat soil (water has a higher heat capacity than soil, ie wet soil will experience a lower increase in temperature than dry soil).		Aquasensor®

Appendix 2 Apparent Conductivity of EM38 Survey of drip irrigated fields at 'Bellevue', Warren.

Experimental site was selected for its relative uniformity based on EM readings. EM readings were collected by NSW Agriculture.



Appendix 3 Experiment site soil description, 'Bellevue', Warren.

Site id: *Bellevue (B1B/B4 boundary)*
Survey job:
Location:
Examiner: *Pat Hulme* Penciller *Ben OBrien*
Date described: *27/4/01*

Soil surface condition: *Hardsetting*
Landform element: *Flat*
Vegetation/crop type:

Depth to (cm)	Horizon	Texture	Structure Grade	Structure Type	Structure Size	SoilPAK -score	Number of roots	Coarse fragment vol	Concretions Type %		Efferves cence	Colour	Mottle colour (moist)	pH	EC	Dispersion	Slaking
11	*Ap*	*LFS*	*Mod*	*Angular blocky*	10/1	0.2	1	0	--	0	*No*	*2.5yr 3/3*	*No*	6	0	2	*Complete*
20	*A3*		*Mod*	*Polthedral*	3-Jan	0.8	2	0	--	0	*No*	*2.5yr 3/3*	*No*	6.5	0	2	*Partial*
33	*B1*	*MC*	*Strong*	*Polthedral*	3-Jan	0.9	1	0	--	0	*No*	*2.5yr 3/3*	*No*	6.5	0	1	*Complete*
70	*B2*	*MHC*	*Strong*	*Polthedral*	3/0.5	1.5	1	0	--	0	*No*	*5yr 5/4*	*No*	7	0	0	*Complete*
120	*B3*	*ZC*	*strong*	*Polthedral*	2/0.5	2	1	0	--	0	*M*	*7.5yr 4/4*	*No*	8	0.2	0	*Partial*

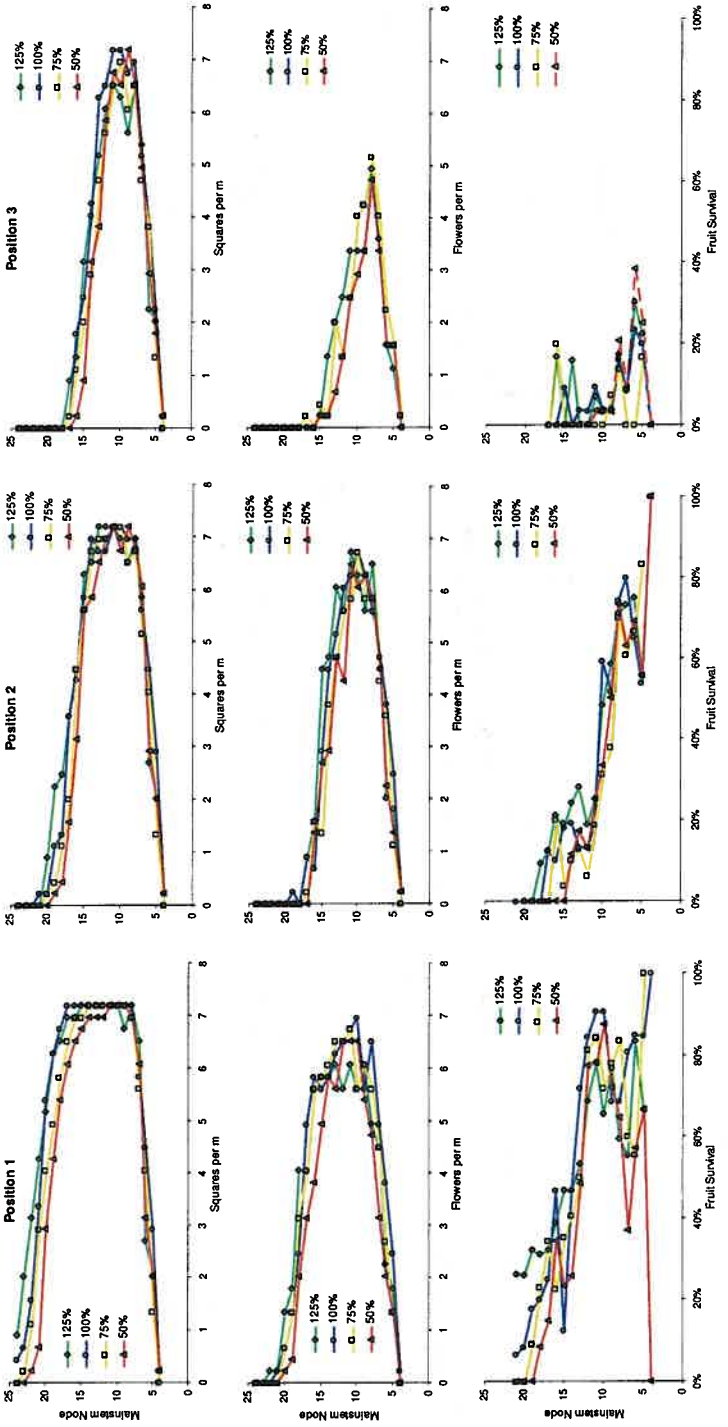
Rootzone: *~20cm*
Permeability: *5-10m*
Drainage: *5*
Comments: *present rootzone ~ 20cm (could be improved to 1m)*
Sporadic A2

Horizon boundaries flat

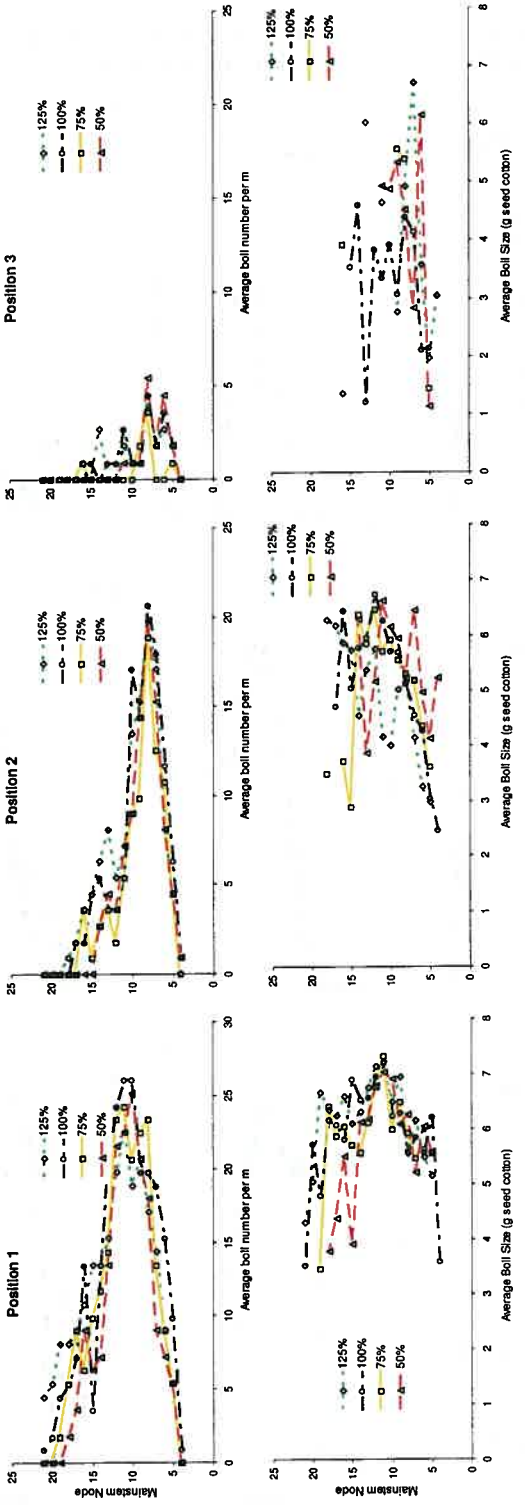
Soil type: *Red Chromosol*

Appendix 4 Fruit count and boll data summaries from the 1999/2000 season.

Fruit count summaries from the 1999/2000 season showing average plant characteristics for number of squares, number of flowers and percentage fruit survival.

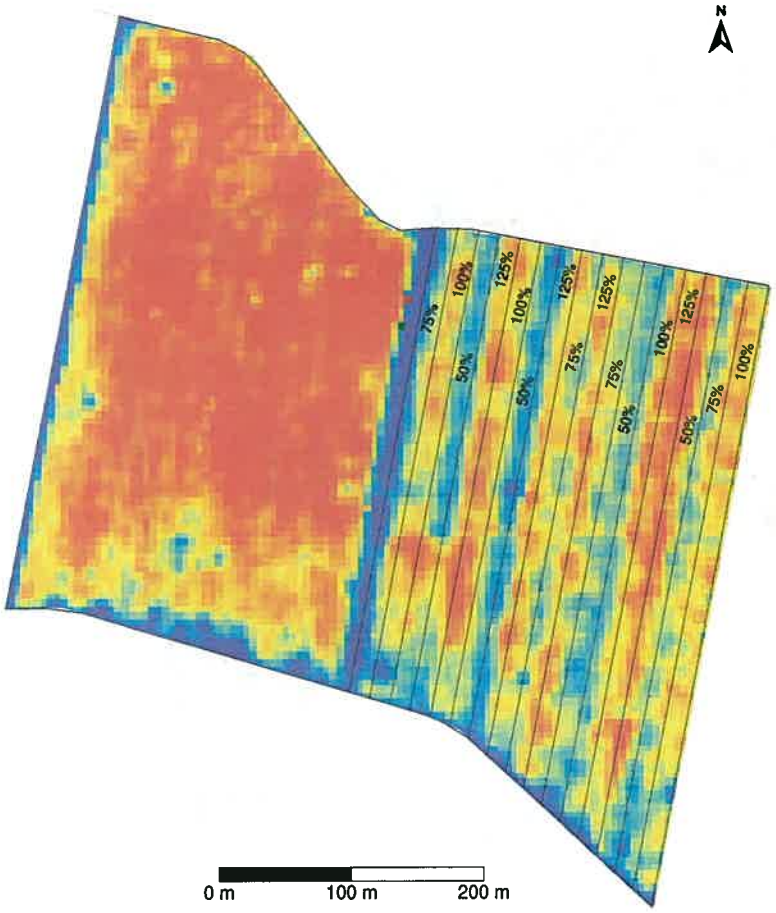


Average boll numbers and boll weights by branch node position (position 1,2 and3) and main-stem node at 'Bellevue', Warren.

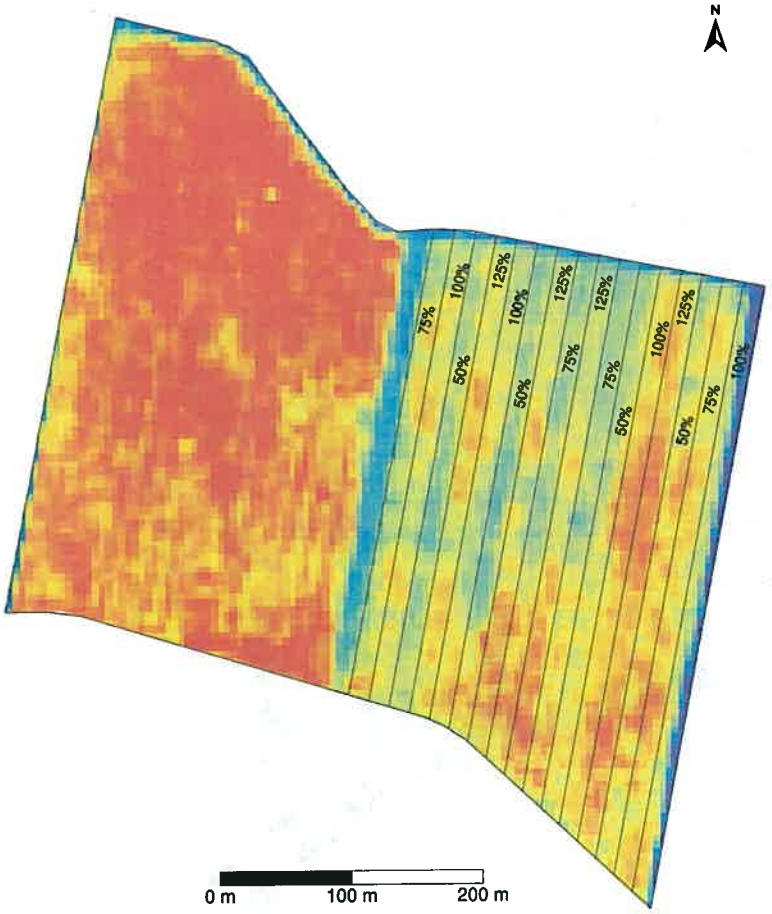


Appendix 5 Cotton yield maps.

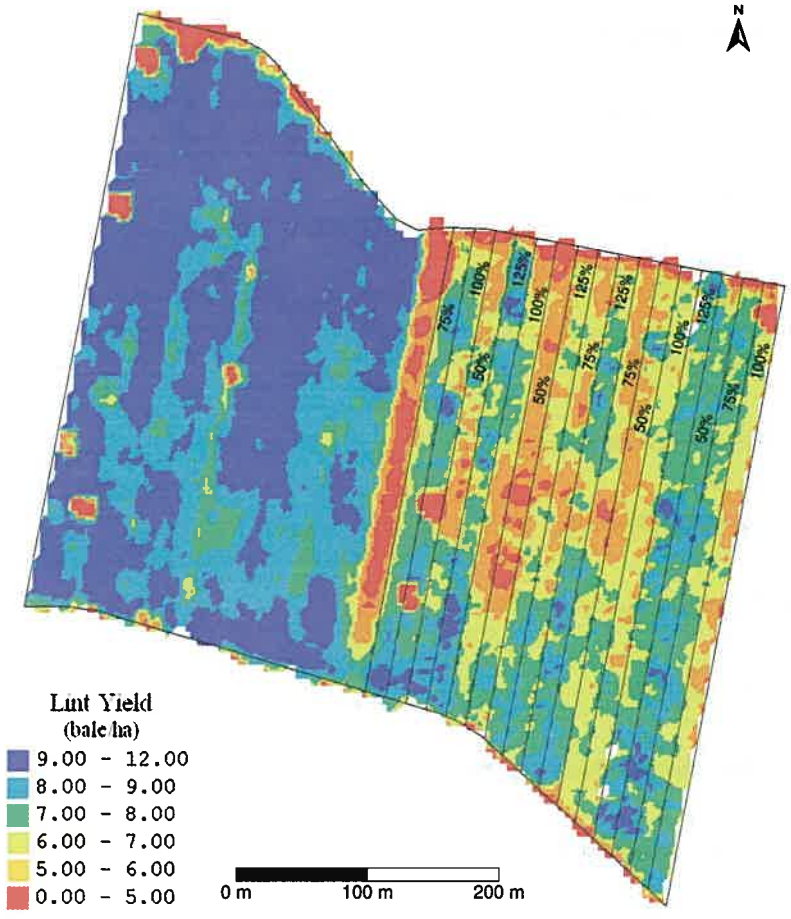
Aerial yield image of experimental area, March 2000. Scale is unknown accept that red colours indicate higher yield and blue lower yield.



Aerial yield image of experimental area, March 2002. Scale is unknown accept that red colours indicate higher yield and blue lower yield.



Estimated yield (2001 harvest) from an Ag Leader yield monitor installed in a cotton picker. Yield monitor has presumed that bales weigh 227 kg and lint out-turn from the cotton gin is 38%.



Appendix 6 Abbreviations

AWC Available Water Content

ET Evapotranspiration

ETcrop Crop Evapotranspiration

FDR Frequency Domain Reflection

Kc Crop Factor

LAI Leaf Area Index

Lsd Least significant difference

LWP Leaf Water Potential

NMM Neutron Moisture Meter

NS Not Significant

PAWC Plant Available Water Content

RAW Readily Available Water

SDI Sub-surface Drip Irrigation